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January 1997

US Army Corps of Engineers
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Repair, Evaluation, Maintenance, and Rehabilitation Research Program

Design Procedure for Geosynthetic Reinforced Steep Slopes

by Dov Leshchinsky, Leshchinsky, Inc.

Prepared for Headquarters, U.S. Army Corps of Engineers

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	Problem Area		Problem Area
CS	Concrete and Steel Structures	EM	Electrical and Mechanical
GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

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Design Procedure for Geosynthetic Reinforced Steep Slopes

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Final report

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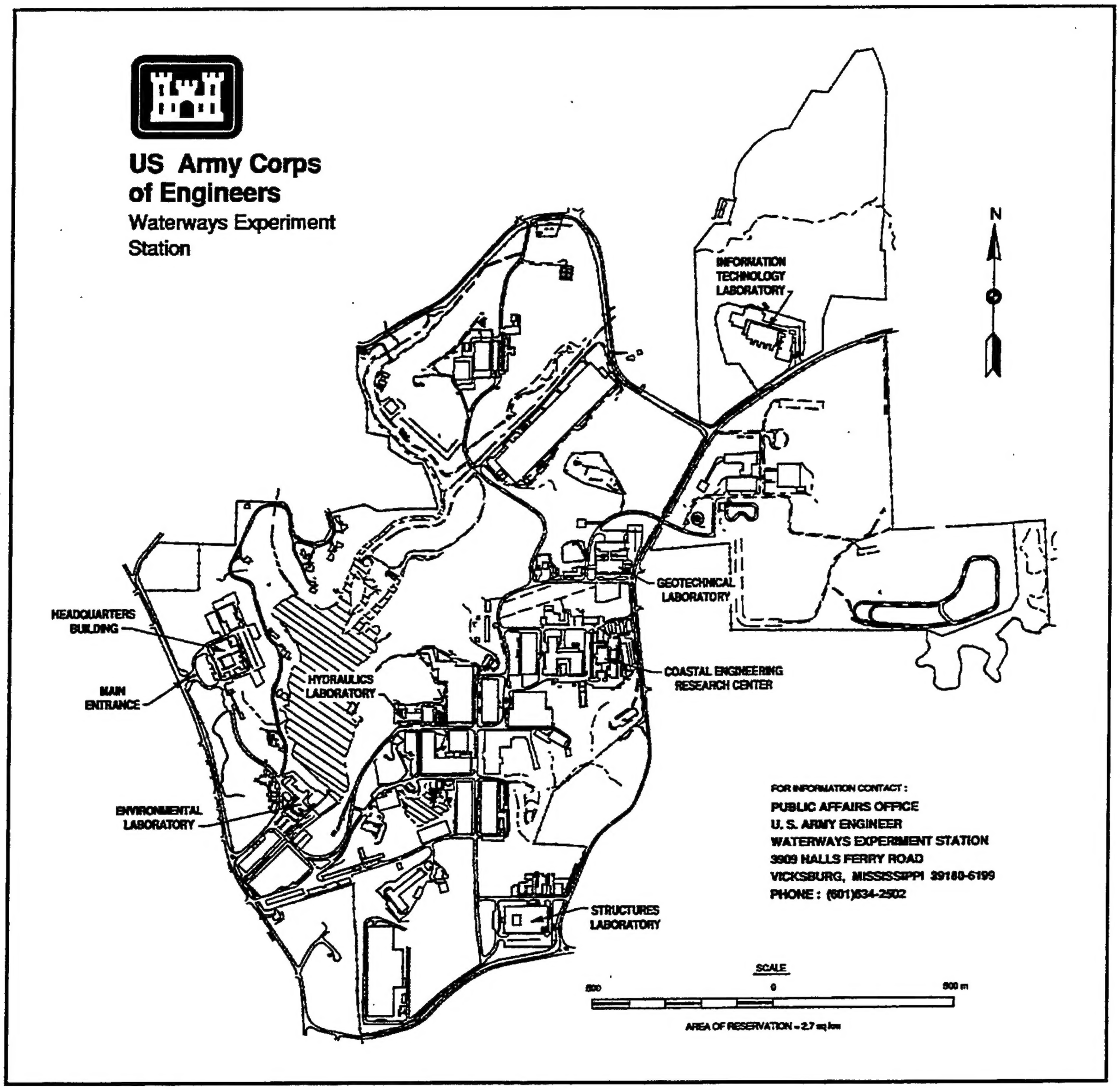

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Preface

The work described in this report was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Geotechnical Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. The work was performed under Civil Works Research Work Unit 32646, "Levee Rehabilitation." The REMR Technical Monitor was Mr. Arthur H. Walz (CECW-EG).

Dr. Tony C. Liu (CERD-C) was the REMR Coordinator at the Directorate of Research and Development, HQUSACE. Mr. Harold C. Tohlen (CECW-O) and Dr. Liu served as the REMR Overview Committee. The REMR Program Manager was Mr. William F. McCleese, U.S. Army Engineer Waterways Experiment Station (WES). Mr. W. Milton Myers, Geotechnical Laboratory (GL), WES, was the Problem Area Leader.

The study was performed by Dr. Dov Leshchninsky, Leshchinsky, Inc., under Contract No. DACW39-94-C-0073 to WES. Dr. Edward B. Perry, Soil and Rock Mechanics Division (S&RMD), GL, was Principal Investigator. The work was conducted under the general supervision of Dr. Don C. Banks, Chief, S&RMD, and Dr. William F. Marcuson III, Director, GL.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. The Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
inches	2.54	centimeters
pounds (force) per foot	14.593904	newtons per meter
pounds (force) per square foot	0.04788	kilopascals
pounds (mass) per cubic foot	0.1570873	kilonewtons per cubic meter

1 Introduction

Soil is an abundant construction material that, similar to concrete, has high compressive strength but virtually no tensile strength. To overcome this weakness, soils, like concrete, may be reinforced. The materials typically used to reinforce soil are relatively light and flexible, and though extensible, possess a high tensile strength. Examples of such materials include thin steel strips and polymeric materials commonly known as geosynthetics (i.e., geotextiles and geogrids). When soils and reinforcement are combined, a composite material, the so-called reinforced soil, possessing high compressive and tensile strength (similar, in principle, to reinforced concrete) is produced.

The increase in strength of the reinforced earth structure allows for the construction of steep slopes. Compared with all other alternatives, geosynthetic reinforced soil slopes are cost-effective. Consequently, various earth structures reinforced with geosynethetics are being constructed worldwide with increased frequency, even in permanent and critical applications (Tatsuoka and Leshchinsky 1994).

This document describes a design process for geosynthetic reinforced steep slopes. It includes the details of the various stability analyses used to determine the required layout and strength of the reinforcing material. To facilitate the design, these analyses were complied into a computer program called ReSlope. This program is user-friendly, and it contains explanations, including graphical illustrations, in response to built-in Help commands. ReSlope is interactive, allowing the user to optimize the design with ease. It accounts for elements such as user-specified partial safety factors, ultimate strength of geosynthetics, cohesive soils, pore-water pressure as determined from a piezometric line, external loads, and seismicity.

ReSlope is written in Fortran and is complied with the Microsoft© PowerStation Complier. This compiler utilizes a 32-bit environment, using memory outside the domain DOS. It achieves this by invoking a DOS extender program, called DOSXMSF, which must be present in the directory path of ReSlope. To run properly, ReSlope requires at least 2MB RAM and a PC compatible system with 386 or higher processor. A math coprocessor is needed to run ReSlope. The program should be run while in the DOS environment. (The program cannot run from DOS prompt in Windows unless a file called DOSXNT.386 is installed and the Windows device driver is

updated. This file can be purchased from Microsoft©.) Typing RESLOPE will invoke the program.

This document provides recommendations regarding the selection of soil shear strength parameters, definitions of the various safety factors, and practical specifications for reinforcement layout. Design aspects related to erosion control and construction are also discussed. Finally, tips regarding arrest of tension cracks and an economical procedure for repairing a failed slope are given.

2 Analyses Used for Design

General

Limit equilibrium (LE) analysis has been used for decades in the design of earth slopes. Attractive features of the LE analysis include experience of practitioners with its application, simple input data, useful (though limited) output design information, tangible modeling of reinforcement, and results that can be checked for reasonableness through a different LE analysis method, charts, or hand calculations. Consequently, extension of LE analysis to the design of geosynthetics reinforced steep slopes is desirable. The main drawback of LE analysis is its inability to deal directly with displacements. However, adequate selection of materials properties and safety factors should assure acceptable displacements, including safe level of reinforcement deformation.

In principle, inclusion of geosynthetic reinforcement in LE analysis is a straightforward process in which the tensile force in the geosynthetic material is included directly in the limit equilibrium equations to assess its effects on stability. However, the inclination of this tensile force must be assumed. Physically, its angle may vary between the as-installed (typically horizontal) and tangent to the potential slip surface. Leshchinsky and Boedeker (1989) and Wright and Duncan (1991) have demonstrated that for cohesionless backfill, this inclination has little effect on both the required strength and the layout of reinforcement. They have shown that for cohesionless soil, horizontal tensil force yields slightly conservative results with respect to the required strength of the geosynthetics. Conversely, Leshchinsky (1992) pointed out that for problems such as reinforced embankments over soft (cohesive) soil, the inclination of the reinforcing geosynthetic, located at the foundation and backfill interface, plays a significant role. Since in manmade reinforced slopes, the *long-term* value of cohesion used in design is typically small, inclination has little effects and therefore, it may be assumed horizontal. The end result then is reasonably conservative with regard to the required tensile strength of the reinforcement.

A potentially significant problem in LE analysis of reinforced soil is the need to know the force in each reinforcement layer at the limit state. Physically, this force may vary between zero and ultimate strength when the slope is at a global limit equilibrium state. Assuming the actual force is known in

advance, as is typically done in *analysis-oriented* computer packages, implies the reinforcement force is actually an *active* one, regardless of the problem. The designer then assumes the active force of each reinforcement layer so that overall limit equilibrium state is obtained. The end result may be a slope in which some layers actually provide more force than their allowable strength, while other layers are hardly stressed. To overcome this potential problem, a rational methodology to estimate the required (i.e., *reactive*) reinforcement tensile resistance of each layer is introduced via a tieback analysis. Consequently, the desiner can verify whether an individual layer is overstressed or understressed, regardless of the overall stability of the slope. Once this problem of local stability is resolved, overall stability of the slope is assessed through rotational and translational mechanisms. In this rotational mechanism (termed in this report as compound failure), slip surfaces emerging beyond the reinforced soil are examined. The force in the geosynthetic layers in this conventional slope stability analysis is taken directly as the maximum allowable value for each layer. The translational analysis (direct sliding) is based on the two-part wedge method in which the passive wedge is sliding either over or below the bottom reinforcement layer, or along the interface with the foundation soil. The following is a brief presentation of the various analyses and a summary of their limitations.

Tieback Analysis

Tieback analysis (also termed internal stability analysis) is used to determine the required tensile resistance of each layer needed to assure a reinforced mass that is safe against internal collapse due to its own weight and surcharge loading. This analysis identifies the tensile force needed to resist the active lateral earth pressure at the face of the steep slope. That is, the tensile force needed to restrain the steep slope from sliding along potential slip surfaces that emerge along the face of the slope. The reinforcement tensile force capacity is made possible through a tieback mechanism in which sufficient anchorage of each layer into the stable soil zone is provided.

Figure 1 shows the notation and convention used in ReSlope. Reinforcement is comprised of primary and secondary layers; however, in analysis only the primary layers are considered. Secondary layers, however, allow for better compaction near the face of the steep slope and thus, reduce the potential for sloughing (Chapter 3). The secondary layers are narrow (typically 3 ft wide) and are installed only if the primary layers are spaced far apart (more than about 2 ft apart). At the slope face, the geosynthetic layers may be wrapped around the exposed portion of the soil mass or, if some cohesion exists, the layers may simply terminate at the slope face as shown in Figure 1. Surcharge loading along the top of the slope may assume three different values as shown in Figure 1. The phreatic surface is defined by a total of four nodes, starting at the origin of the coordinate system (i.e., the toe of the slope and extending into the slope). Each of the soils (i.e., reinforced soil,

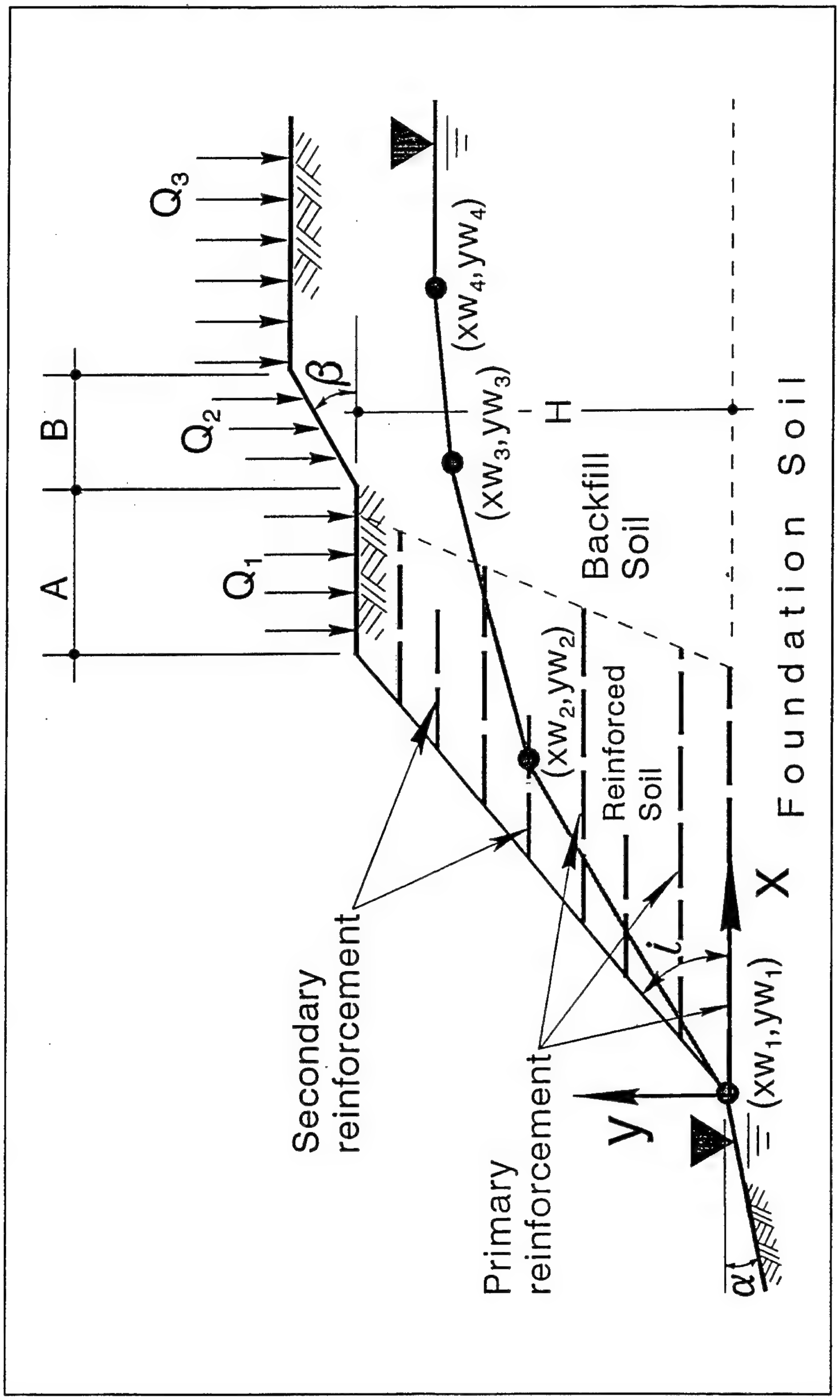


Figure 1. Notation in ReSlope

backfill soil, and foundation soil) may possess different shear strength properties.

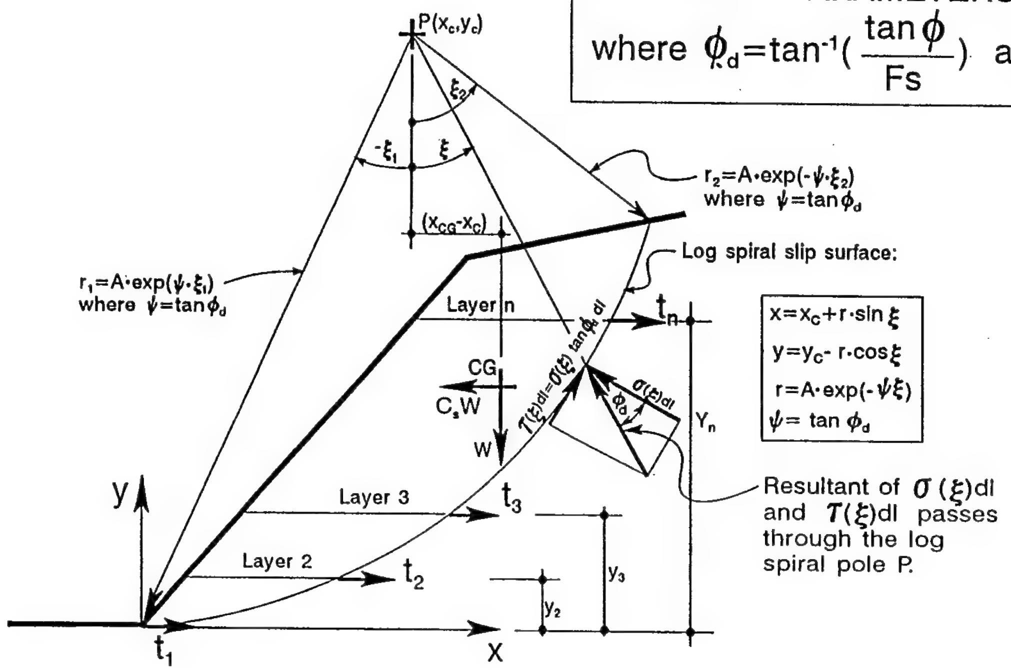
In this report, steep slopes are defines as slopes inclined at angles for which they are considered unstable without reinforcement. For example, with granular backfill, a slope would be considered steep if its inclination is steeper than its angle of repose (i.e., $i > \phi_d$ where i and ϕ_d are the slope inclination and angle of repose, or design friction angle, respectively). Consequently, in steep slopes the force in each reinforcement layer is activated by an unstable soil mass. That is, the reactive force in each reinforcement layer has to restore a limit equilibrium state. To determine the location of the critical shear surface and subsequently, the necessary reaction force, a log spiral failure surface has been selected. This mechanism is frequently used in geotechnical stability problems.

The log spiral mechanism makes the problem statically determinate. For an assumed log spiral failure surface which is fully defined by the parameters x_c, y_c, and A (e.g., see inset in Figure 2 or Appendix A for definition of terms), the moment equilibrium equation about the pole can be written explicitly without resorting to assumptions in statics. Consequently, by comparing the driving and resisting moments, one can check whether the mass defined by the assumed log spiral is stable for the design values of the shear strength parameters: ϕ_d *and* c_d and the distribution of reinforcement force t_j . This check is repeated for other potential log spiral failure surfaces until the least stable system is found, i.e., until the critical slip surface and the associated maximum required restoring reinforcement force are found. The term C_s (Figure 2) is the seismic coefficient introducing a pseudo-static force component. It acts at the center of gravity of the critical mass. No surcharge is shown in Figure 2 for the sake of clarity of presentation; however, inclusion of its effects in the moment equilibrium equations is straightforward. In this case, C_s is also applied to the surcharge load, rendering a horizontal pseudo-static force at the crest, where the surcharge acts.

Figure 3 illustrates the computation scheme for estimating the tensil reaction in each reinforcement layer. In Step 1, the soil acting against D_n is considered. Note that D_n is signified by a reinforcement layer wrapped around the slope face (Figure 3), thus making it physically feasible for a mass of soil to be laterally supported, resulting in a locally stable mass. That is, D_n is considered as a facing unit (i.e., an imaginary facing plate on the front edge of the reinforced soil mass) preventing slides of unstable soil above that tend to emerge through it. This facing is capable of providing lateral support through the development of tensile force in the geosynthetic. The moment equilibrium equation is used to find the critical log spiral producing $max(t_n)$ employing the free-body diagram shown in Figure 3 while examining many potential surfaces. The resulted t_n counterbalances the horizontal pressure against D_n and, thus, signifies the reactive force in layer *n*. That is, the resulted t_n represents the force needed to restore equilibrium and hence stability. Note that D_n was chosen to extend down to layer *n*. This tributary area implies a toe failure which activates the largest possible reaction force.

STRENGTH PARAMETERS OF SOIL: ϕ_d, c_d

where $\phi_d = \tan^{-1}\left(\dfrac{\tan\phi}{Fs}\right)$ and $c_d = \dfrac{c}{Fs}$



Moment about P is independent of $\sigma(\xi)$ distribution over the log spiral and therefore, can be written explicitly without resorting to assumptions in statics:

$$+\sum M_p = 0: \quad W(x_{CG}-x_C) + C_s W(y_C - y_{CG}) - c_d \int (x-x_c)\,dy - c_d \int (y_c - y)\,dx + \int u(x-x_c)\,dx - \int u(y_c-y)\,dy - \sum_{j=1}^{n} t_j (y_C - y_j) = 0$$

Figure 2. Log spiral slip surface: static equilibrium implications

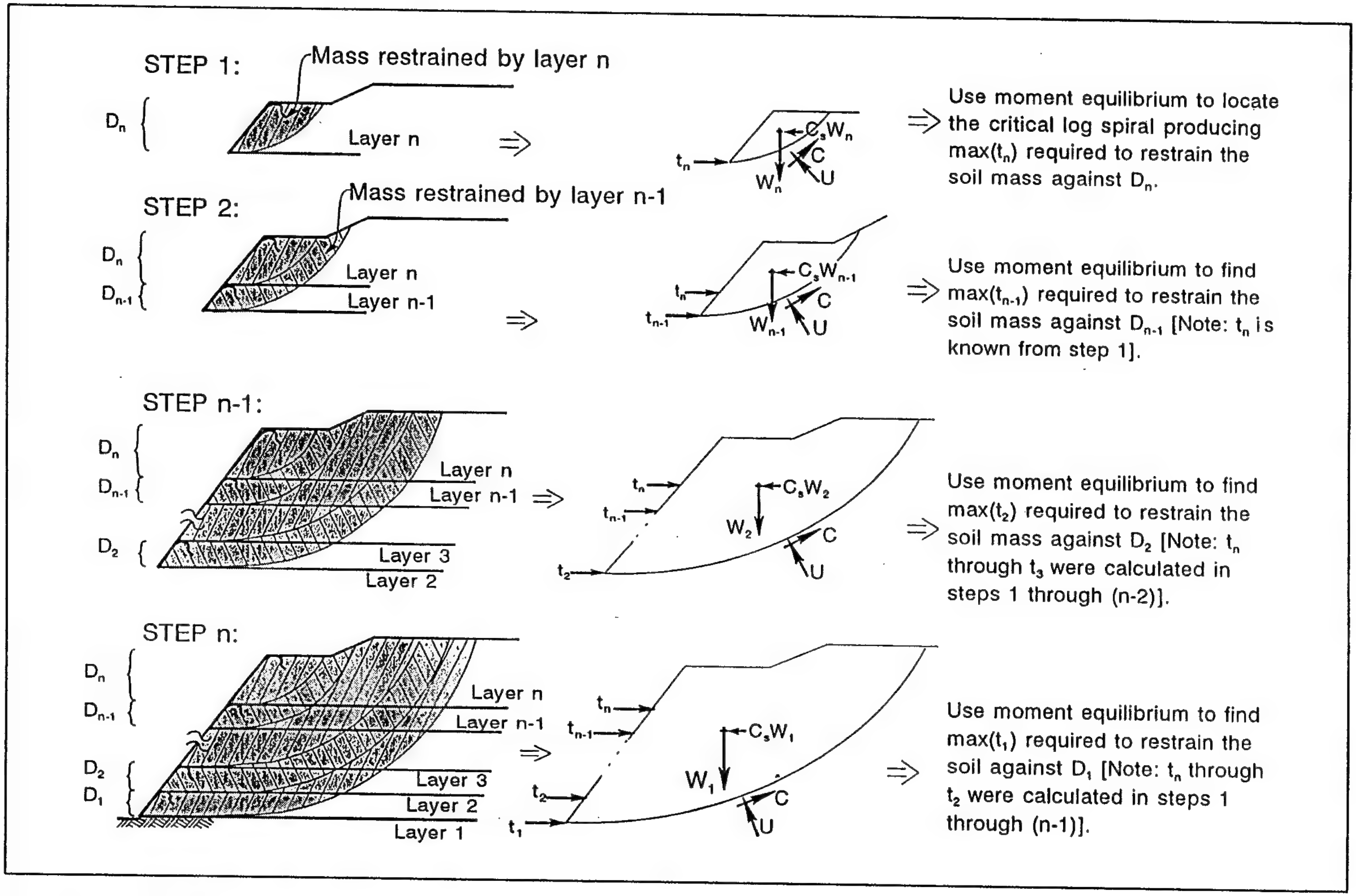


Figure 3. Tensile reaction in reinforcement: computation scheme

In Step 2, the force against D_{n-1} is calculated. D_{n-1} extends from layer *n* to layer *(n-1)*. Using the moment equilibrium equation, $max(t_{n-1})$, required to retain the pressure exerted by the unstable soil mass against D_{n-1}, is calculated. When calculating t_{n-1}, the reaction t_n, determined in Step 1, is known in magnitude and point of action. Hence, the reactive force in layer *(n-1)* is the only unknown to be determined from the moment equilibrium equation.

Figure 3 shows that by repeating this process, the distribution of *reaction* forces for all reinforcing layers, down to t_1, is calculated while supplying the demand for an LE state at each reinforcement level. Application of appropriate safety factors should assure long-term stability at each level.

Note that cohesive *steep* slopes are stable up to a certain height. Consequently, the scheme in Figure 3 may produce zero reaction force in top layers. Though these layers may not be needed for local stability (or tieback), they may be needed to resist compound failure as discussed in the next section.

The outer-most critical log spiral defines the extreme surface as dictated by *Layer 1*. In conventional tieback analysis it signifies the extent of the *active zone*; i.e., it is the boundary between the sliding soil mass and the stable soil. Consequently, reinforcement layers are anchored into the stable soil to assure their capacity to develop the calculated tensile reaction t_j (Figure 4). In the next section, however, it is shown that the *stable* soil may not be immediately adjacent to this outer-most log spiral and therefore, some layers should be extended further to assure satisfactory stability.

Note in Figure 3 and 4 that the reinforcement layers are wrapped around the overlying layer of soil to form the slope face. However, in slopes that are not as steep (say, $i < 50°$), typically there is no wrap around the face or any other type of facing. In this case, load transfer from each unstable soil mass to the respective reinforcement layer is feasible due to a coherent mass formed at the face. This mass is formed by soil arching, by a trace of cohesion and closely spaced reinforcement layers. The end result is a soil plug, in a sense similar to the one developed at the bottom of a driven open-end pile, that acts *de facto* as a facing unit, thus making feasible the load transfer into the primary reinforcement layer. It should be pointed out that closely spaced reinforcement does not necessarily mean closely spaced *primary* reinforcement layers; simply, this plug can be created by the combination of secondary and primary layers working together to create a coherent mass. Since reinforcement layers, including primary and secondary layers, are spaced approximately 1 ft apart, and since the secondary layers extend at least about 3 ft into the slope, the contribution of secondary layers to the formation of a *facing* should not be ignored. With time, surface vegetation and its root mat enhances this *facing*. The end result of forming a coherent face is not just an efficient load transfer from the deep unstable soil mass to the reinforcement, but also improved surficial stability and erosion resistance.

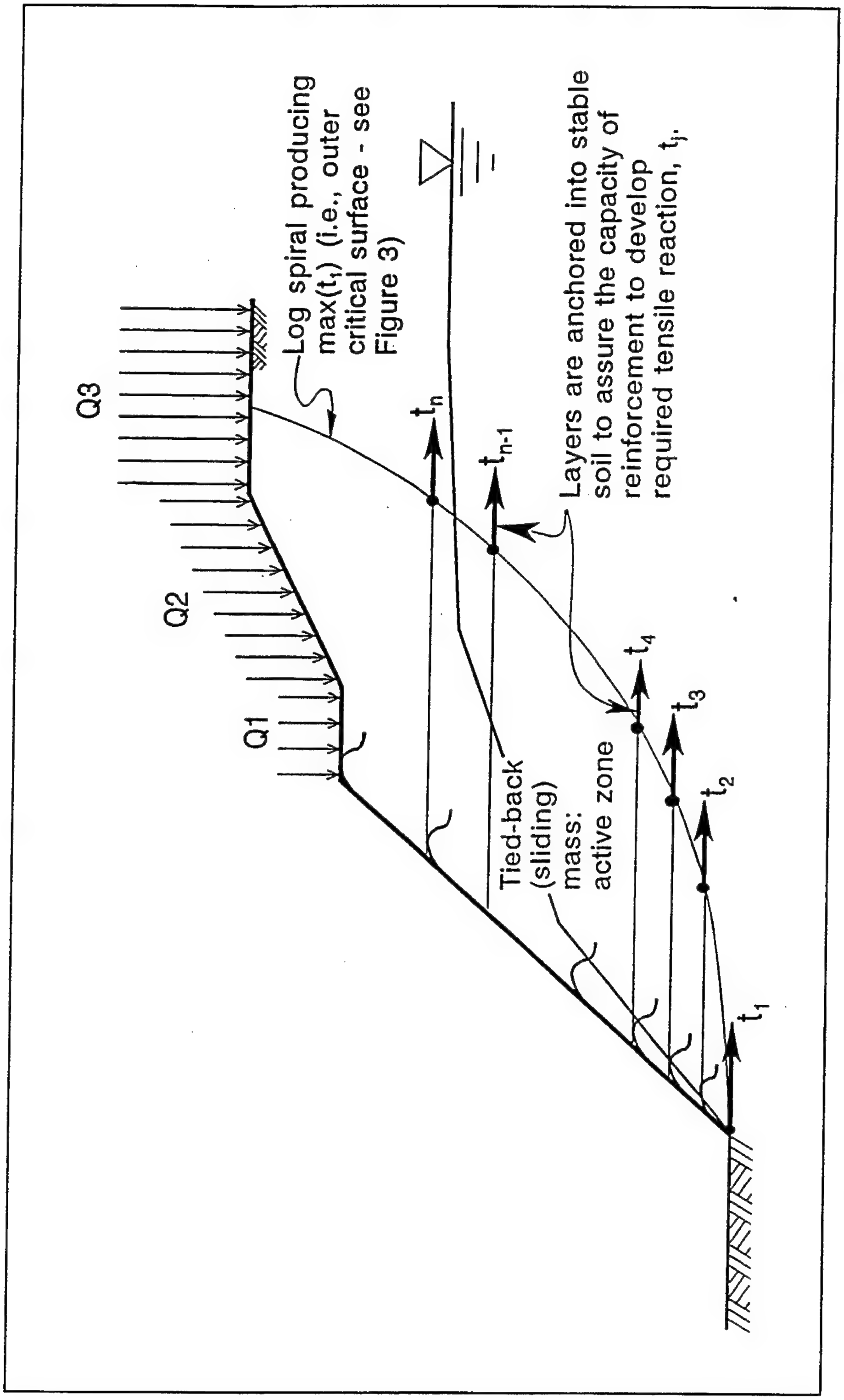


Figure 4. Transfer of tensile reaction into soil adjacent to active zone

Compound Stability Assessment

For a given geometry, pore-water pressure distribution and (ϕ_d *and* c_d) the tieback analysis provide the required tensile resistance at the level of each reinforcement layer. It also yields the trace of the outer-most log spiral defining the active soil zone, a notion commonly used in conjunction with analysis of retaining walls. In reinforced wall structures, the capacity of the reinforcement to develop the required tensile resistance depends also on its pullout resistance; i.e., the length anchored into the stable soil zone. If the boundary of this stable zone is indeed defined by the active one, then potential slip surfaces that are passing further into the soil mass than the outer-most log spiral (outside or within the effective anchorage length) will never be critical. However, since such surfaces will render reduced pullout resistance capacity, they may produce an unstable system. Consequently, a conventional slope stability analysis is used to determine the required reinforcement length so that compound failures will not be likely to occur.

The conventional factor of safety in LE is also utilized in ReSlope; i.e., $F_s = tan(\phi_{available})/tan(\phi_{design}) = c_{available}/c_{design}$ (general note in Figure 5). Note that the terms ϕ_{design} and c_{design} are equivalent to, or interchangeable with, the *mobilized* shear strength parameters. The specified minimum value of $F_{s(design)}$ for soil shear strength in ReSlope must be satisfied for all rotational slip surfaces, whether tieback or compound.

The tieback analysis results in the required allowable strength of reinforcement at each level. The specified reinforcement, therefore, must possess strength equal or exceeding this calculated strength. In reality, the allowable strength of most layers will exceed the required value as determined from the tieback analysis. Consequently, if viewed from global stability, only m layers are needed (Step 1 in Figure 5); i.e., reinforcement selected based on tieback analysis may produce more reinforcement than needed for global stability. These bottom m layers may contribute their full allowable strength in the compound analysis where only the aspect of global stability is examined. The upper layers $(m+1)$ through n are assumed (conservatively) to be capable of contributing only their calculated tieback values.

Embedding the layers immediately to the right of the outer-most log spiral obtained in the tieback analysis, so that $t_{allowable}$ for layers 1 through m and t_j for layers $(m+1)$ through n could develop through pullout resistance, will produce a system having a factor of safety in excess of $F_{s(design)}$. Terminating the upper layers $(m+1)$ through n at points ABC in Figure 5 will decrease the factor of safety. However, since the summation of $t_{(allowable)j}$ for the outer-most log spiral equals or exceeds the required overall value (Step 1 in Figure 5), the resulting safety factor is equal to or slightly larger than $F_{s(design)}$. Consequently, these upper layers are sufficiently long.

Following a procedure similar to the one detailed by Leshchinsky (1992), lengthen layers 1 through m to a test body defined by a log spiral extending between the toe and the crest, deeper than the outer-most log spiral (Step 2 in

GENERAL : In LE analysis one must assure that for all possible slip surfaces, the following F_S is exceeded:

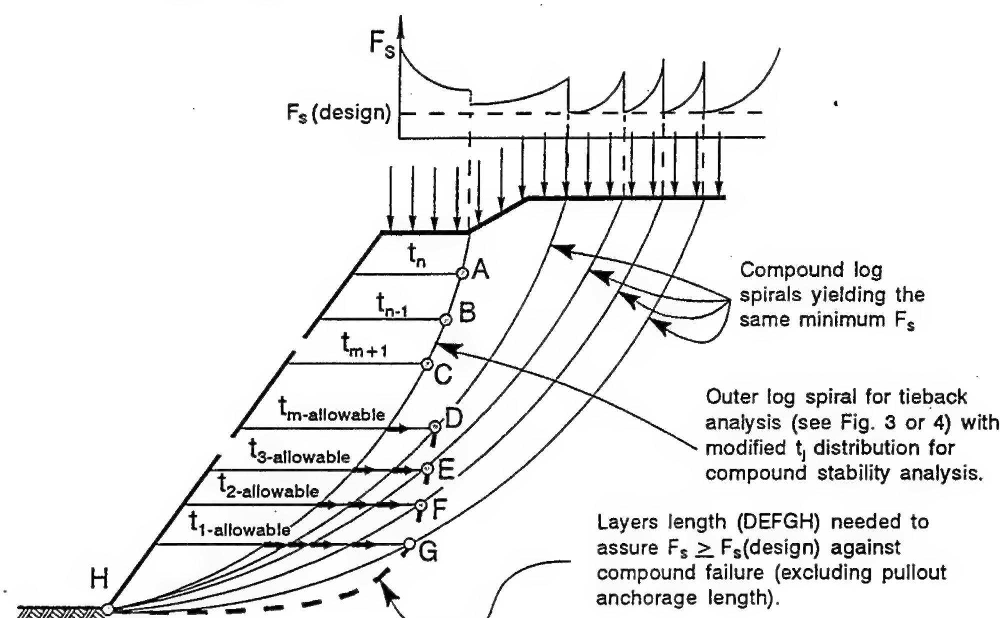
$$\min(F_S) = F_S(\text{design}) = \frac{\tan(\phi_{\text{available}})}{\tan(\phi_{\text{design}})} = \frac{C_{\text{available}}}{C_{\text{design}}}$$

NOTE: $\phi_{\text{design}} = \phi_{\text{mobilized}}$, $C_{\text{design}} = C_{\text{mobilized}}$

STEP 1: Find m so that $\sum_{j=1}^{m} (t_{\text{allowable}})_j \geq \sum_{j=1}^{n} t_j$

where m = minimum number of layers, counting from bottom layer #1, capable of developing total tensile resistance equal to the total force, for all reinforcement layers, as obtained from tieback analysis.

STEP 2: Conduct stability analysis according to the following scheme:



STEP 3: Repeat Step 3 for slip surface emerging at Layer 2, then Layer 3 and so on, up to Layer n.

STEP 4: The longest length (including anchorage) from Steps 2 and 3 is selected for design, assuring adequate resistance to both tieback and compound failures.

Figure 5. Reinforcement length required to assure compound stability

Figure 5). Embed each layer beyond the slip surface so that $t_{(allowable)j}$ can develop. F_s will increase as slip surfaces deeper than the critical one are specified. Truncate layer m and check (using the moment equilibrium equation) whether F_s has dropped to the minimum design value. If it has, this layer is sufficiently long (point D in Figure 5); if it is less than the minimum,

lengthen this layer and repeat calculations until a satisfactory length is found. ReSlope repeats this process to determine the required length of layer *(m-l)*, while considering zero contribution from all layers above since they were already truncated. That is, layers above are not effective for deeper slip surfaces. Subsequently, point *E* is found. Repeating the process for all layers down to layer *l* yields the length (e.g., curve *DEFGH* in Figure 5) required to assure that the minimal value of F_s is met or exceeded for all possible log spiral failure surfaces emerging through the toe.

Compound critical surfaces emerging above the toe are also possible. ReSlope verifies that the length of reinforcement will produce safety factors exceeding $F_{s(design)}$ for potential slip surfaces emerging above the toe. As indicated in Step 3 in Figure 5, the scheme shown in Step 2 is repeated for slip surfaces emerging through the slope face. The values of t_j then are taken as determined in Step 2. Subsequently, layers previously truncated will be lengthened, if necessary, to produce a satisfactory safety factor.

At this point, it is appropriate to elaborate on some terminology used in ReSlope. In its output, the following controlling mode of failure appears next to each layer: *Compound Mode of Failure or Tieback Mode of Failure*. The first mode implies the *full* allowable strength of layer *j* was utilized in analysis to assure resistance to compound failure. In this case, the reinforcement force required for tieback stability is smaller than that required for compound failure and therefore, the compound failure is considered critical (i.e., prevailing). The second mode indicates that only the tensile force required to assure local stability, as obtained from tieback analysis, was needed. Required anchorage length of each layer is then calculated according to the layer's prevailing mode of failure and its associated tensile force. For an adequately designed slope, bottom layer(s) should always correspond to a compound failure. Tieback mode of failure at bottom layer(s) indicates the factor of safety for uncertainties specified by the designer is unattainable for the selected reinforcement and its spacing. The designer then must either specify a stronger or more closely spaced reinforcement. Alternating modes of failure in ReSlope also indicate inadequate specified strength or spacing of reinforcement.

Anchorage lengths are specified beyond points *A, B, C, D, E, F, G,* etc. This is slightly conservative since, contrary to the compound analysis exact procedure, it assures that $t_{allowable}$ can also develop along the envelop *D, E, F,* and *G*, although zero strength is required there. However, since the required anchorage lengths of lower layers are relatively short in realistic problems, this simplification is reasonably conservative. In fact, since pullout resistance depends on overburden pressure that is calculated in an approximated fashion (i.e., the weight of soil column and surcharge above the point of interest, per unit area, is calculated as this pressure), such conservatism is warranted.

Specifying a layout similar to the envelope *ABCDEFG* will contain, at least, *m* potential slip surfaces, all having the same minimal safety factor against rotational failure (Figure 5). However, because of practical

considerations, a uniform or linearly varying length of layers is specified by ReSlope (based on Step 4 in Figure 5). As a result, the number of such potential slip surfaces is reduced in the actual structure since most layers are longer, and typically, some are stronger than optimally needed. ReSlope displays only the most extreme compound surface; all other potential compound surfaces are augmented between the outer-most tieback surface and this outer-most compound surface.

Finally, anchorage lengths are calculated to resist pullout forces equal to the required allowable strength of each layer multiplied by a factor of safety $F_{s\text{-}po}$. In these calculations, the overburden pressure along the anchored length and the parameter defining the shear strength of the interface between soil and reinforcement are used. This parameter, C_i, termed the interaction coefficient, relates the interface strength to the reinforced soil design strength parameters: $tan(\phi_d)$ and c_d. The interaction coefficient is typically determined from a pullout test. An American Society for Testing Materials (ASTM) standard does not exist yet for this test. However, very clear details about the procedure, data reduction, and significance of the pullout test are given by Koerner (1994), pp 338 through 341. The required anchorage length of layer j then equals $t_j \div \{\sigma_j . C_j . [tan(\phi_d) + c_d]\}$ where σ_j signifies the average overburden pressure above the anchored length.

Direct Sliding Analysis

Specifying reinforcement layout that satisfies a prescribed F_s against rotational failure does not assure sufficient resistance against direct sliding of the reinforced mass along its interface with the foundation soil or along any reinforcement layer. The length required to assure stability against such failure, L_{ds}, is determined from an LE analysis that satisfies force equilibrium; i.e., the two-wedge method.

An initial value of L_{ds} is first assumed (Figure 6). Then, a value for δ, the interwedge force inclination, is chosen: δ may be specified between zero and ϕ_d of the backfill or reinforced soil, whichever is smaller. Subsequently, the maximum value of the interwedge force, P is found by varying θ while solving the two force equilibrium equations for the active *Wedge A*. This interwedge force signifies the resultant of the lateral earth pressure exerted by the backfill soil on the reinforced soil. Next, the vertical force equilibrium equation for *Wedge B*, which includes the vertical component of the lateral thrust of the active wedge (i.e., $Psin\delta$), is solved. After obtaining N_B, the sliding resisting force, T_B, along the base L_{ds} is calculated.

When calculating T_B, the coefficient C_{ds} is utilized; it signifies the interaction coefficient between the reinforcement and the soil as determined from a direct shear test. If the bottom layer (i.e., layer 1 in Figure 3) is placed directly over the foundation soil, two values of C_{ds} are needed: one for the interface with the reinforced soil and the other for the interface with the

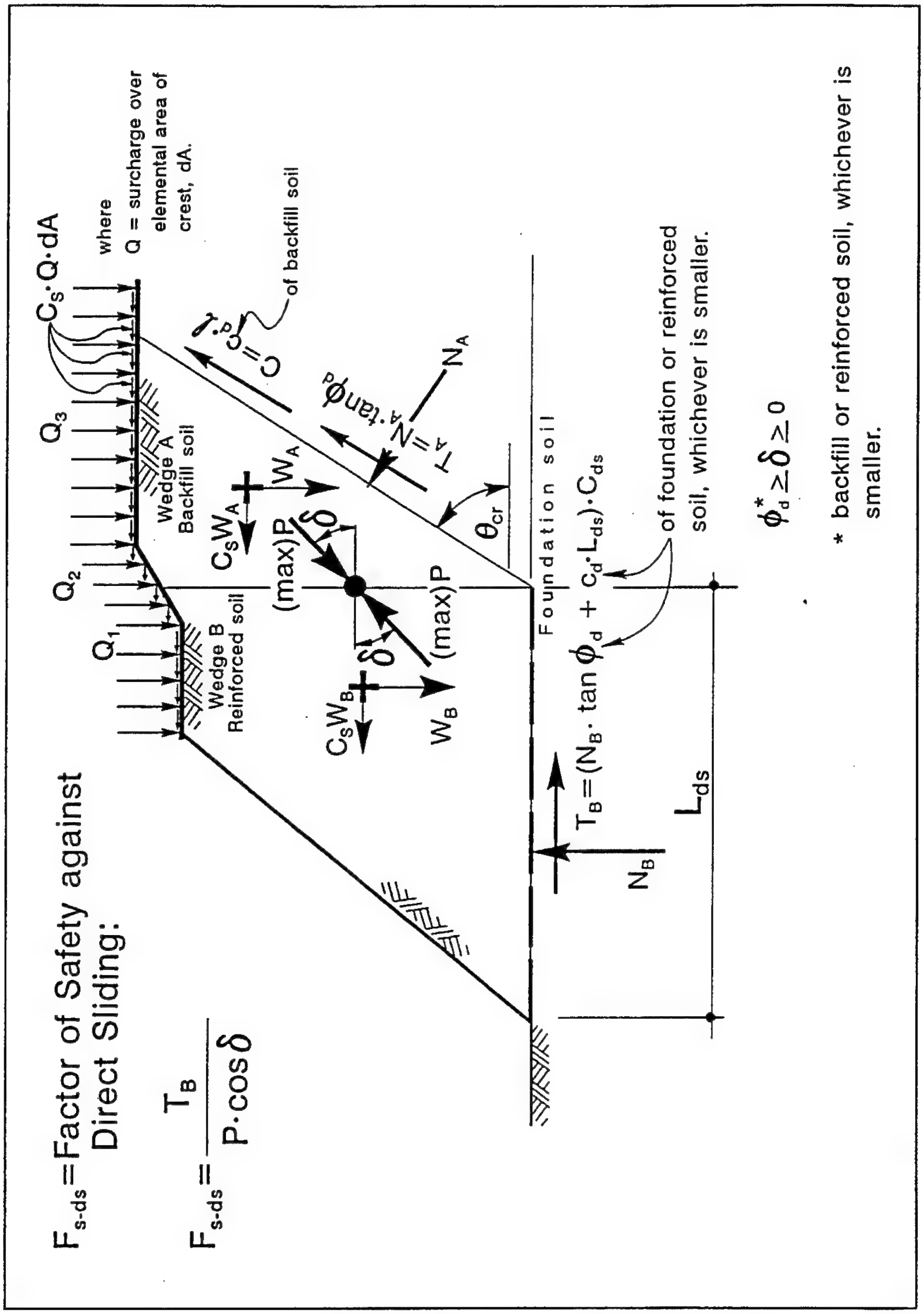


Figure 6. Two-part wedge mechanism for direct sliding analysis

foundation soil. If the bottom layer is above the foundation, ReSlope will ignore the value specified for the interface with the foundation soil; however, it will check stability for direct sliding along the interface between the reinforced and foundation soils, as well as along the reinforcement embedded within the reinforced soil.

At this stage, the actual factor of safety against direct sliding of the reinforced mass, $F_{s\text{-}ds}$, can be calculated by comparing the resisting force with the driving force; i.e., $F_{s\text{-}ds} = T_B \div cos\delta$. This factor of safety corresponds to the assumed value of L_{ds}. ReSlope changes L_{ds}, repeating the process for *Wedge A* and *Wedge B*, until the computed factor of safety against direct sliding is equal to the prescribed value. L_{ds} reported by ReSlope corresponds to the maximum length obtained from analysis of sliding along the foundation soil (if bottom layer is placed above the foundation) and from analysis of sliding above and below bottom layer.

The assumed value of δ may have significant influence on the outcome of the analysis. Selecting $\delta > 0$ implies the backfill soil will either settle relative to the reinforced soil or the reinforced soil will slide slightly as a monolithic block thus allowing interwedge friction to develop. Since the effects of reinforcement layers, some of which will typically intersect the interwedge interface, are ignored, selecting a value of δ in between $(2/3)\phi_d$ and ϕ_d should be viewed as a conservative choice.

The technique for incorporating seismicity into the force equilibrium analysis is shown in Figure 6. In a pseudo-static approach, however, large seismic coefficient, C_s, may produce unrealistically large reinforced soil block, *Wedge B*. In this case, a permanent displacement type of analysis (i.e., Newmark's stick-slip model) is recommended. Alternatively, ReSlope allows the user to eliminate inertia from *Wedge B*, analogous, in a sense, to the Mononobe-Okabe model used in analysis of gravity walls. Only the 'dynamic' effects on P are superimposed then on the statics of the problem. Unlike Mononobe-Okabe who used the static θ_{cr} also for the dynamic case, ReSlope seeks and uses θ_{cr} producing maximum interwedge force, *max(P)*.

Finally, note that $F_{s\text{-}ds}$ is imposed after reducing the shear strength parameters of the soils by a factor of safety; i.e., using ϕ_d and c_d. In the context of LE slope stability analysis, this constitutes a double taxation. However, in the analysis of reinforced slopes, notions associated with reinforced walls are commonly used, including the value of $F_{s\text{-}ds}$. To be consistent with this practice, ReSlope allows the user to specify $F_{s\text{-}ds}$. For most slopes, its specified value should range between 1.0 and 1.3.

Deepseated Analysis Using Bishop Method

ReSlope performs conventional slope stability analysis, utilizing Bishop method, to assess the minimum factor of safety against deepseated failure. In a sense, this analysis indicates the bearing capacity of the foundation soil.

Circular slip surfaces are examined and the one rendering the lowest factor is selected. The circles examined, however, are restricted to those passing away from the bottom of the reinforce soil zone. The stabilizing effects of intersecting reinforcement layers above the bottom layer with the critical circle

are ignored. The maximum feasible penetration is set by the user. Circles describing overhanging cliffs are excluded from considered. In case of a backslope, a tension crack is introduced between the crest and the elevation of the top of the slope. Seismicity is included in the analysis through the coefficient C_s. That is, Bishop's formulation was modified to include pseudo-static forces due to self weight and surcharge loads.

Deepseated circles tend sometimes to emerge rather steeply. It is well known that in this case, large numerical errors may occur in slope stability methods utilizing slices. ReSlope tests for such potential error through a parameter known as m_α. If $m_\alpha < 0.1$ for a slice, the slide resistance of this slice is set to zero.

ReSlope does not adjust automatically the length of bottom reinforcement layers to meet a certain factor of safety against deepseated failure. In case this factor is less than an acceptable minimum, the user can use the following procedure. Set larger than needed safety factors for direct sliding. This will result in longer reinforcement length and subsequently, larger factor of safety against deepseated failure; i.e., it will push the critical circle away thereby increasing the associated safety factor. Repeat until a satisfactory factor is attained. Before significant lengthening of the reinforcement, however, it is worthwhile to check whether Bishop analysis for the particular problem does not produce overly conservative results. This check can be done using one of the available rigorous slope stability methods (e.g., Spencer's, Janbu's, or Morgenstern-Price's). To avoid over conservatism, stabilizing effects of reinforcement layers intersecting the slip surface should then be included in the analysis.

Limitation of Analyses

Though the analyses in ReSlope follow a rational scheme in the context of design, the following limitations should be highlighted:

a. In the compound failure analysis, only log spirals emerging at or above the toe were considered. That is, log spirals emerging away from the toe, signifying deepseated failures that activate the reinforcement, were excluded. Toe and above toe potential slip surfaces are typically most critical in steep slopes, especially when the foundation soil is competent. An indication regarding the competency of the foundation in ReSlope is provided by the Bishop deepseated analysis. Furthermore, since the trace of the outer-most compound slip surface is displayed by ReSlope, one can render a judgment whether deepseated failure through the reinforcement is likely to occur. That is, if this surface is deep (though emerging through the toe) and if the foundation soil strength properties are similar to, or lower than, the reinforced soil, then the critical compound slip surface is likely to be deeper than the one predicited by ReSlope. In this case, a more generalized analysis such as UXTEXAS3 is advised (see Edris and Wright 1992; Edris, Munger,

and Brown 1992). However, such deepseated failures will require extremely strong and long reinforcement rendering, perhaps, an uneconomical reinforced slope.

b. The phreatic surface (Figure 1) can be estimated from a flow net. However, ReSlope utilizes it as a piezometric line to assess the pore-water pressure distribution. That is, the depth of a point relative to this line is used to calculate the pressure. In the strict sense of flow nets, equipotential lines are used to calculate the pressure distribution. Using the phreatic surface as a piezometric surface yields slightly more conservative results (i.e., the calculated pressures are somewhat larger than those predicted by a flow net). It should be added that if piezometric data are available, one can establish the location of the surface termed 'phreatic' in ReSlope in a straightforward manner. Finally, as is the case in most stability analysis computer programs, *seepage* forces are assumed to be negligible.

c. The possibility of surficial failure is not assessed by ReSlope. If the reinforcement is wrapped around at the slope face, this type of failure is not likely to occur (provided the backfolded geosynthetic sheet is reembedded sufficiently deep, usually at least 3 ft away from the slope face). If no backfolding is specified (as is typical for slopes inclined at less than 50 deg,) secondary reinforcement and proper erosion control measures (including vegetation) should be used to minimize the risk of surficial failure.

d. In the strict sense of analysis, the log spiral slip surface is valid for homogenous soil only. However, in the compound failure analysis (Figure 5), this surface passes through both reinforced and backfill soils and possibly, even through the foundation soil. ReSlope is using a weighted average technique, considering the compound failure lengths in the reinforced soil and in the backfill soil, to find equivalent values for ϕ_d and c_d to be used in analysis. The value of the equivalent ϕ_d is used to define the trace of the log spiral passing through the reinforced and backfill soils. The weighted average is such that the results will be somewhat on the conservative side.

e. For low strength of backfills, a segment of the outer-most compound failure may pass through the foundation soil. The strength of soil used in analysis then is approximated as described in item *d*. That is, the strength of the foundation is not considered in the averaging. However, if the foundation soil is relatively strong, such penetration is unlikely. ReSlope allows the user to limit the extent of critical slip surface to just being tangent, at most, to the foundation. The end result then is much shorter length of reinforcement as dictated by compound analysis. The user should use judgement when invoking this option. If the foundation soil is quite soft, deep compound failures are feasible (see discussion in item *a*).

f. Figure 1 shows three different intensities of surcharge loads: Q_1, Q_2, and Q_3. However, the predicted reinforcement force obtained from the *tieback analysis* will theoretically be more accurate as the loads above the trace of the outer-most tieback surface (Figure 4) approach uniformity. The reason for a potential inaccuracy when the loads are grossly nonuniform can be realized using the scheme in Figure 3. Each layer counterbalances a distinctive slice of soil. The slice may be subjected to surcharge load. Consequently, each portion of surcharge over a particular slice is solely counterbalanced by a single reinforcement layer. If this surcharge is quite concentrated (i.e., distributed over a few slices), only a few layers will react to this surcharge. However, since soil medium tends to distribute and diminish such surcharge loads with depth, these few layers will actually be subjected to lower forces while layers above and below (i.e., outside the tributary area defined by the surcharge slices) will carry higher loads than those predicted by the tieback analysis. That is, concentrated loads may lead simultaneously to both conservative and unconservative predictions regarding reactive forces in reinforcement layers. In the rare occasion when a problem involving high intensity Q_2 or Q_3 over the outer-most tieback surface is analyzed, use the following approximating procedure. Run ReSlope twice. First, run it without surcharge to obtain baseline results for the reactive force in the reinforcement layers, then run it with the actual surcharge to obtain the required length of layers. Use an available approximate solution to estimate the lateral earth pressure against each tributary area (Figure 3) due to the concentrated surcharge. Calculate the resultant force over each tributary area resulting from this lateral pressure. Add each resultant force (i.e., superimpose) to the existing force in each respective layer as calculated in the first run (i.e., the surcharge free run). The factor of safety for uncertainties, for the tieback mode of failure, can be calculated now for each layer. A safe layout, including adequate resistance to compound failure and direct sliding, has been obtained from the second run. The user is likely to find that in slopes less than about 60 deg the alternative more 'accurate' procedure has negligible effects on the results.

3 Design Considerations

General

The analyses in ReSlope are all based on a limiting equilibrium state. Such a state deals, by definition, with a structure that is at the onset of failure. Adequate safety factors included in the analyses ensure acceptable margins of safety against the various failure mechanisms analyzed. It is implicity assumed in the LE analysis that the different materials involved (i.e., the geosynthetic materials and soils) will all contribute their full design strengths simultaneously. For materials having a constant plastic shear strength after some deformation, sùch as assumption is realistic. However, the materials in the reinforced soil system do not possess this idealized plasticity. Consequently, the following guide is recommended when specifying material properties for ReSlope analysis.

Soil Shear Strength and Factor of Safety

Slip surface development in soil is a progressive phenomenon, especially in reinforced soil where reinforcement layers delay the formation of a surface in their vicinity. That is, a slip surface does not develop simultaneously along its full length and thus, the peak shear strength of the compacted soil is not being mobilized simultaneously as assumed in the LE analysis. Consequently, it is recommended that the design values of ϕ and c will not exceed the residual strength of the soil. This will assure that at the state of a fully developed failure, the shear strength utilized in each analysis is indeed attainable all along the slip surface.

The value of the shear strength parameters reported by laboratories typically correspond to *peak* shear strength. In this case, a minimum factor of safety of $F_s = 1.3$ practically assures that the design strength parameters will be at or below their residual values [i.e., $\phi_d = tan^{-1}\ (tan\phi_{peak})/F_s$ and $c_d = c_{peak}/F_s$]. It is recognized that by using the residual values, the gain in soil strength due to compaction is basically ignored in the analysis and thus, has an overall conservative impact on the reinforced slope. However, the complex issue of progressive failure is then avoided while assuring results on

the safe side. Usage of residual strength in analysis should not undermine the importance of compaction for structural performance.

There are cases in which the soil will not exhibit a peak strength behavior. If the soil is lacking peak strength characteristics or the reported shear strength corresponds to a residual value, a factor of safety of $F_s = 1.0$ can then be used. Note that for residual shear strength parameters, a value of $F_s = 1.0$ is typically specified in design of critical structures such as geosynthetic reinforced walls. Though such a value seems to be low, recall that the stability of a steep slope is hinging on the tensile strength of the reinforcement; that is without reinforcement a slide will occur. The soil just contributes its shear resistance to slide.

If cohesive fill is used, extreme care should be used when specifying the cohesion value. Cohesion has significant effects on stability and thus the required reinforcement strength. In fact, a small value of cohesion will indicate that no reinforcement at all is needed at the upper portion of the slope. However, over the long run cohesion of manmade embankments tends to drop and nearly diminish. Since *long-term* stability of reinforced steep slopes is of major concern, it is perhaps wise to ignore the cohesion altogether. It is therefore recommended to limit the design value of cohesion to 5 kPa. It should be pointed out, however, that end-of-construction analysis must be also conducted if a soft foundation is present. In this case stability against deepseated failure must be assured.

Safety Factors Related to Geosynthetics

Limit equilibrium analysis assumes that the reinforcement and soil will reach their design strengths at the same instant, regardless of deformation characteristics. Though employment of residual strength will assure availability of the soil shear resistance at all deformation levels, this may not be the case with the reinforcement. For example, if the reinforcement is very stiff relative to the soil, its strength will be mobilized rapidly, potentially reaching its design value before the soil reaches its strength. This may lead to overstressing and subsequently, premature rupture of the reinforcement, violating the premise that its tensile resistance will be available with the soil strength. The result might be local, or even global, collapse. However, since geosynthetics are ductile (typically, rupture strain greater than 15 percent), large strains will develop locally in response to overstressing, thus allowing the soil to deform and mobilize its strength as assumed in the analysis and as needed for stability.

To assure that indeed some overstressing of the reinforcement without breakage is possible, a *factor of safety for uncertainties* is specified in ReSlope. This factor multiplies the calculated minimal required reinforcement strength at each level. Typical values for this factor range from $F_{s\text{-}u} = 1.3$ to 1.5. The strength of the factored reinforcement should be available

throughout the design life of the structure. To achieve this, partial safety factors for installation damage ($F_{s\text{-}id}$), creep ($F_{s\text{-}cr}$), and biological ($F_{s\text{-}bd}$) and chemical ($F_{s\text{-}cd}$) degradation should be applied so that geosynthetics possessing adequate ultimate strength, t_{ult}, could be selected. That is, the specified geosynthetic should have the following ultimate strength:

$$t_{ult} = t_{required} \cdot (F_{s\text{-}u}) \cdot (F_{s\text{-}id}) \cdot (F_{s\text{-}cr}) \cdot (F_{s\text{-}bd}) \cdot (F_{s\text{-}cd})$$

Preliminary values for the partial safety factors in slope reinforcement applications are given by Koerner (1994):

	Geogrids	Geotextiles
$F_{s\text{-}id}$	*1.1 to 1.4*	*1.1 to 1.5*
$F_{s\text{-}cr}$	*2.0 to 3.0*	*2.0 to 3.0*
$F_{s\text{-}bd}$	*1.0 to 1.3*	*1.0 to 1.3*
$F_{s\text{-}cd}$	*1.0 to 1.4*	*1.0 to 1.5*

Note that for normal soil condition (i.e., near neutral pH and no biological activity) in steep slopes, either chemical or biological degradation should not be a problem when using a typical reinforcing polymeric material. The values of $F_{s\text{-}id}$, $F_{s\text{-}bd}$, $F_{s\text{-}cd}$ are site specific. The creep safety factor, $F_{s\text{-}cr}$, depends, to a large extent, on the polymer type and the manufacturing process.

Documented testing on geosynthetics, to be provided by the manufacturer or supplier, will likely result in recommended safety factors falling within the range suggested by Koerner (1994), as shown in the tabulation above. When actual test documentation is not available, however, the following *conservative* default values are recommended (Berg 1992):

$$F_{s\text{-}id} = 3.0,\ F_{s\text{-}cr} = 5.0,\ F_{s\text{-}bd} = 1.3,\ and\ F_{s\text{-}cd} = 2.0$$

The following provisions apply to these default values:

a. A creep default value may be used only for preliminary design; actual test data are required for final design.

b. A chemical default value should not be used for these soils: acid sulphate soil, organic soil, salt-affected soil, ferruginous soil, calcareous soil, and modified soils (e.g., soils subjected to deicing salts, and cement stabilized or lime stabilized soils); actual test data should be used for final design.

Documented test data on creep test results should comply with ASTM D 5262-92 (ASTM 1992a) test procedure. The term *ultimate strength*, t_{ult},

should correspond to the result obtained from the wide-width tensile test, following ASTM D 4595-86 (ASTM 1986) procedure. Note that the selected geosynthetic should be installed so that its ultimate strength is available in the potential slide direction (i.e., geosynthetics typically possess different strengths along their principal axes). Typically, the strength at 5 percent elongation strain in the wide-width test is reported as well. Some designers concerned with performance prefer to use this value as t_{ult}. In this case, the factor of safety for uncertainties can be reduced to $F_{s\text{-}u}$ = 1.1 to 1.3, since the true ultimate strength is significantly larger. It should be noted, though, that performance (i.e., deformations) of steep slopes is less critical than that of walls and therefore, the 5 percent limit is unnecessary for most practical purposes.

To make the design process more efficient, ReSlope requires the user to specify the ultimate strength of each reinforcement layer. For the selected spacing and strengths, ReSlope reports whether the resulted minimum factor of safety for uncertainties is satisfactory. To be practical, the user should input a realistic value of ultimate strength. A convenient source for such values is available in the *Specifier's Guide*, published annually in the *Geotechnical Fabrics Report* by the Industrial Fabrics Association International, 345 Cedar Street, St. Paul, Minnesota 55101, Tel. (612) 222-2508. This publication also includes the addresses of manufacturers. The user can then verify further data related to recommended (and documented) partial safety factors corresponding to a product.

Finally, if seismicity is considered in the design via specification of a seismic coefficient in ReSlope, the factor of safety against creep can be reduced by as much as 50 percent. Simply, since the duration of the superimposed pseudo-static seismic load is short, significant creep is not an issue. However, the user should run ReSlope again, this time with no seismicity, to verify that the required seismic strength is no less than the required value for static stability where the creep safety factor is high; the larger strength value from static and seismic runs should be specified.

Other Specified Safety Factors

ReSlope requires as input data the factor of safety against direct sliding, $F_{s\text{-}ds}$. This safety factor assures that the force tending to cause direct sliding of the reinforced soil block is adequately smaller than the force available to resist it. It is a straightforward adaptation of analysis from reinforced retaining walls or gravity walls. However, in slope stability analysis, unlike walls, the shear strength parameters of the soil are reduced by F_s. It is recommended to use $F_{s\text{-}ds}$ = 1.3 if the soil safety factor, F_s, is 1.3 or less. For large specified values of F_s (i.e., values rendering shear strengths less than the residual strengths), the values for $F_{s\text{-}ds}$ should range from 1.0 to 1.3.

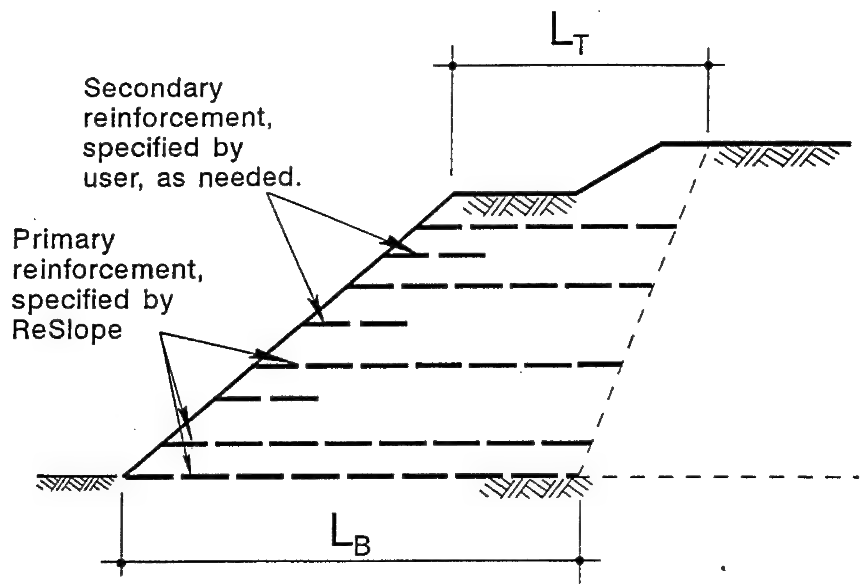
With reference to direct sliding, note the coefficient C_{ds} related to this mechanism. There are two direct sliding coefficients. The first signifies the ratio of shear strength of the interface between the reinforcement and reinforced soil and the shear strength of the reinforced soil alone. The second coefficient signifies a similar ratio but with respect to the strength of the foundation soil. This coefficient reflects a mechanism in which soil slides over the reinforcement sheet. Its value can be determined by using direct shear tests in which the shear strength of the interface between the relevant type of soil and the reinforcement is assessed under various normal loads. The test procedure is described in ASTM D 5321-92 (ASTM 1992b). To avoid the dilemma of the development of progressive failure, it is once again recommended that one use the residual strength values for both interface strength and soil strength when calculating their ratio C_{ds}. Typically, C_{ds} will vary between 0.5 and 1.0, depending on the type of soil and reinforcement. For granular soils and common geosynthetics used in reinforcement, C_{ds} is about 0.8. Beware that in many cases the required length of bottom layer (i.e., see L_B in Figure 7) may increase significantly as C_{ds} decreases below 0.8.

The user-specified factor of safety against pullout, $F_{s\text{-}po}$, should multiply the calculated required allowable tensile force of each reinforcement layer. Anchorage length then is calculated to provide pullout resistance up to this increased tensile force. Typically, $F_{s\text{-}po}$ value is specified as 1.5.

Similar to C_{ds}, ReSlope requires the value of C_i, the interaction coefficient. It relates the strength of the interface between the reinforcement and soil to the shear strength of the reinforced soil or foundation soil. This coefficient reflects a mechanism in which the reinforcement is being pulled out from a confining stable soil. The required anchorage length is calculated based on C_i. This value C_i is normally determined from a pullout test; for test details refer to Koerner (1994), pages 338 through 341. Typically, the value of C_i varies between 0.5 and 1.0, depending on the type of soil and reinforcement. For granular soils, the typical value of C_i is about 0.7. It should be pointed out that anchorage length for reasonably spaced (e.g., 1- to 2-ft vertical spacing) continuous reinforcing sheets, the typical anchorage length is quite small relative to the total required length in the final layout. The user can easily conduct a parametric study for a particular problem using ReSlope to verify whether a sophisticated procedure to determine accurately C_i is indeed worthwhile.

Specified Layout of Reinforcement

Two practical options for specifying reinforcement length are available in ReSlope (Figure 7). The first option simplifies construction by specifying all layers to have a uniform length. This length is selected as the longest value obtained from either the tieback analysis, the compound failure analysis, or the direct sliding analysis.



ReSlope Options:

(1) $L = L_T = L_B =$ longest length required for tieback analysis, compound failure analysis, and direct sliding analysis.

(2) $L_B =$ same as L in (1).

$L_T =$ longest length required for tieback analysis and compound failure analysis.

Figure 7. Reinforcement length specified by ReSlope

The second safe option is to specify L_B and L_T at the bottom and top, respectively, where L_B is the longest length from all analyses and L_T is the longest length obtained from compound and tieback analyses. Length of layers in between is linearly interpolated. This specification is more economical; however, it may result in misplaced layers at the construction site. ReSlope allows the designer to select uniform (option 1) or nonuniform (option 2) lengths.

Figure 7 shows primary and secondary reinforcing layers. In the stability analyses, only primary layers are considered. However, layers spaced too far apart may promote localized instability along the slope face. Therefore, secondary reinforcement layers should be used. Their width should extend at least 3 ft back into the fill and their strength, for practical purposes, may be the same as the adjacent primary reinforcement. The vertical spacing of a secondary reinforcement layer from either another secondary layer or from a primary one should be limited to 1 ft. Secondary reinforcement creates a coherent mass at the slope face, a factor important for local stability. Furthermore, it allows for better compaction of the soil at the face of the steep slope. This, in turn, increases the sloughing resistance and prevents surficial failures. If wraparound is specified (necessary in very steep slopes), secondary reinforcement can be used to wrap the slope face as well. It should be backfolded then at least 3 ft back into soil, same as the wrapping primary reinforcement.

Erosion Control

Erosive forces can cause surface sloughing, especially when steep slopes are considered. Consequently, measures to minimize erosion damage must be part of the design process of a reinforced slope system.

The most common method to reduce erosion due to surface water runoff is through use of vegetation. However, establishment and maintenance of vegetative cover over steep slopes can be difficult (Berg 1992). For example, the steepness of the grade limits the amount of water absorbed by the soil before runoff occurs and thus makes it more difficult for germination and establishment of roots. Furthermore, established vegetation must be maintained over the entire slope throughout time.

An effective way to control erosion is to use synthetic mats or blankets. To be considered permanent, the mat should be stabilized against ultra-violet radiation and be inert to naturally occurring soil-born chemicals and bacteria. As pointed out by Berg (1992), the erosion control mat serves three functions: (a) protects the bare soil face against erosion until vegetation is established, (b) reduces runoff velocity for increased water absorption by the soil thus promoting long-term survival of the vegetative cover, and (c) reinforces the root system of the vegetative cover. Note that maintenance of vegetation (e.g., reseeding, mowing, etc.) may be required and, therefore, should be considered in design when specifying the slope angle.

For slopes that are less than 45 deg, low-height slopes, and/or moderate runoff, a permanent synthetic mat may not be required (Berg 1992). A degradable erosion blanket may be specified to promote growth until vegetative cover is firmly established. Such a blanket will typically lose its integrity after about 1 year.

Most manufacturers' literature provides detailed installation guidelines for erosion blanket and mats. As a rule, mats/blankets should be placed over a smooth and compacted grade that is covered by a few inches of topsoil. Anchor trenches should secure the mat/blanket at the upstream and downstream ends; these trenches should be at least 12 in. deep and 6 in. wide (Figure 8). Note that U-shaped ground staples are used in Figure 8 to fasten the blanket to the surface. If the slope is longer than approximately 30 ft, the blanket/mat should be secured by embedding it in slots, maximum 30 ft apart, 6 in. deep and 6 in. wide (Figure 9). Details regarding overlapping, edge anchor, staple patterns, and seeding are given by manufacturers according to their product properties and experience. Note that prices vary widely. Product suitability for a specific project should be verified by the designer. Upon selection of a product, the designer should specify the layout and installation details.

Tension Cracks

When cohesive soil is used for steep slopes, tension cracks are likely to develop at the crest. This likelihood increases when the soil is compacted above its optimal moisture content, as is the typical case in levee construction.

Using Mohr-Coulomb's failure criterion, it can be shown for $\phi = 0$ that the depth to which tensile normal stresses extend, Z_c, approximately equals $2c/\gamma$ where c = cohesion and γ = moist unit weight of soil.

To reduce the probability of a tensile crack development, several techniques can be used. Placing a granular soil cover, Z_c thick, over the crest will provide sufficient overburden pressure to eliminate tensile stresses within the clayey soil. The granular cover should be considered as a surcharge load, $Q = \gamma \cdot Z_c$, in the stability analysis and design. A more practical solution would be to install geogrid layers, spaced at 6-in. intervals, within the tensile stress zone Z_c. These grid layers should be placed along the entire crest width. The minimum allowable strength of these grids should exceed $t_{allowable} > c \cdot Z_c / n$ where n = number of grid layers within Z_c. If this strength is less than that required for the primary reinforcement layers, it will be less confusing at the construction site to use the same strength as the primary layers. Such usage of geogrids will arrest the development of cracks. The end result will be tension cracks with negligible depth.

Slope Repair

Reinforced soil can be used effectively to repair failed slopes. To lower the cost of repair, minimum excavation into the remaining stable portion of the slope is desired; i.e., the collapsed material is removed and a minimal cut into the undamaged slope is conducted so that the exposed slope is sufficiently

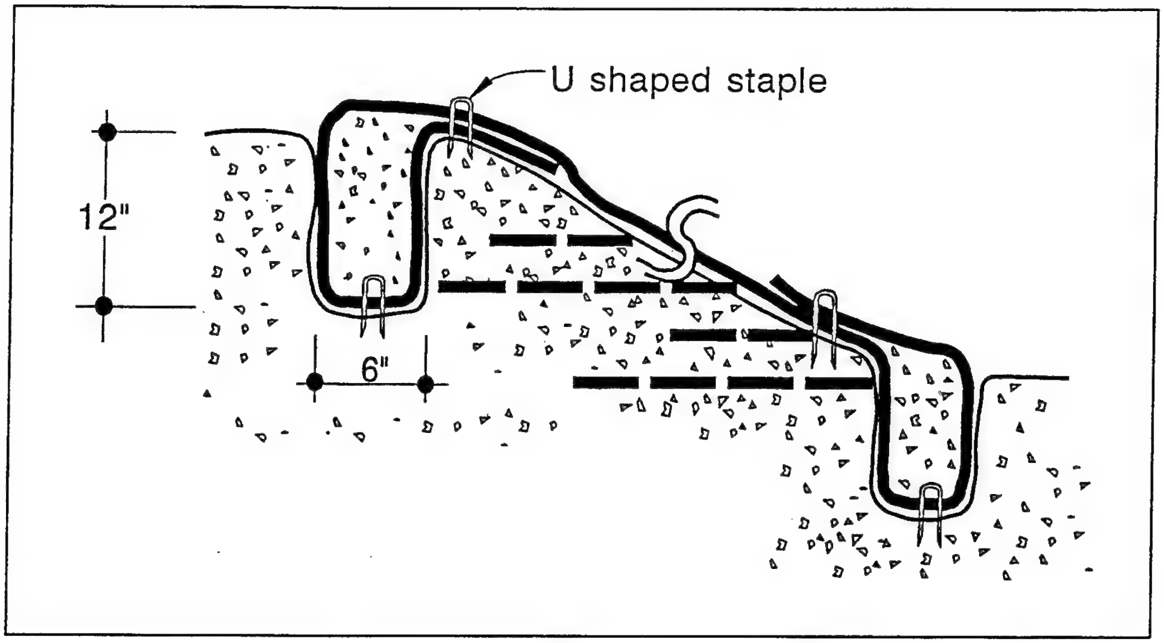


Figure 8. Erosion control mat embedded at top and bottom of slope

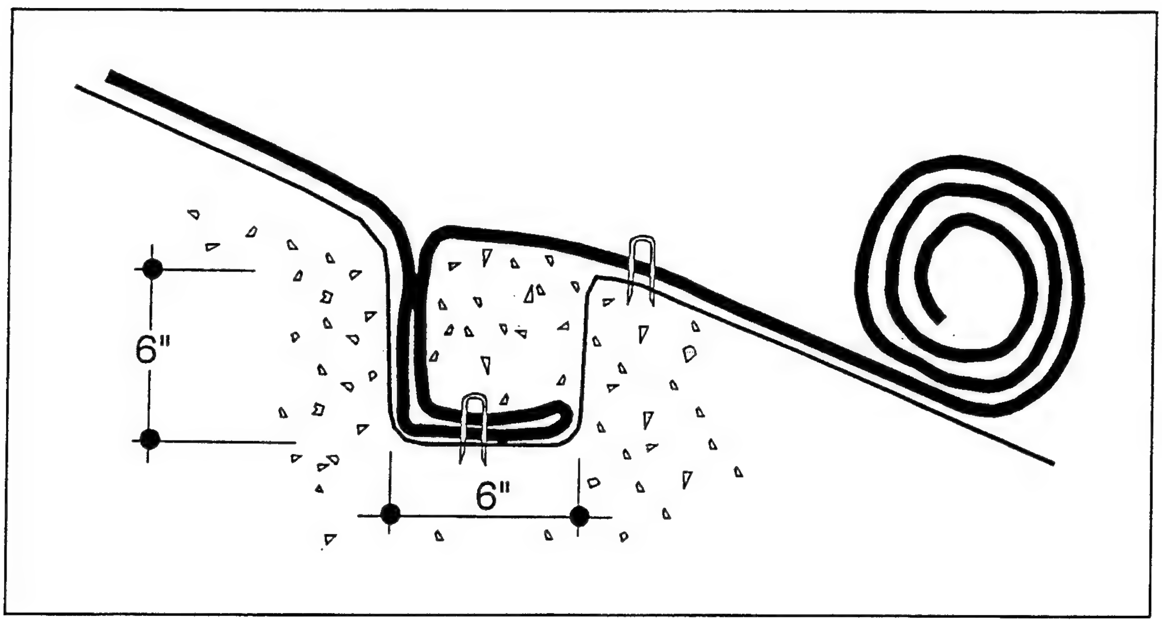


Figure 9. Erosion control mat secured at intermittent intervals

stable during the repair (Figure 10). Such a process implies that the length of bottom reinforcement layers are restricted in length. However, ReSlope provides the unrestricted length of grids as obtained from analysis. To make use of ReSlope for restricted reinforcement length, follow this procedure:

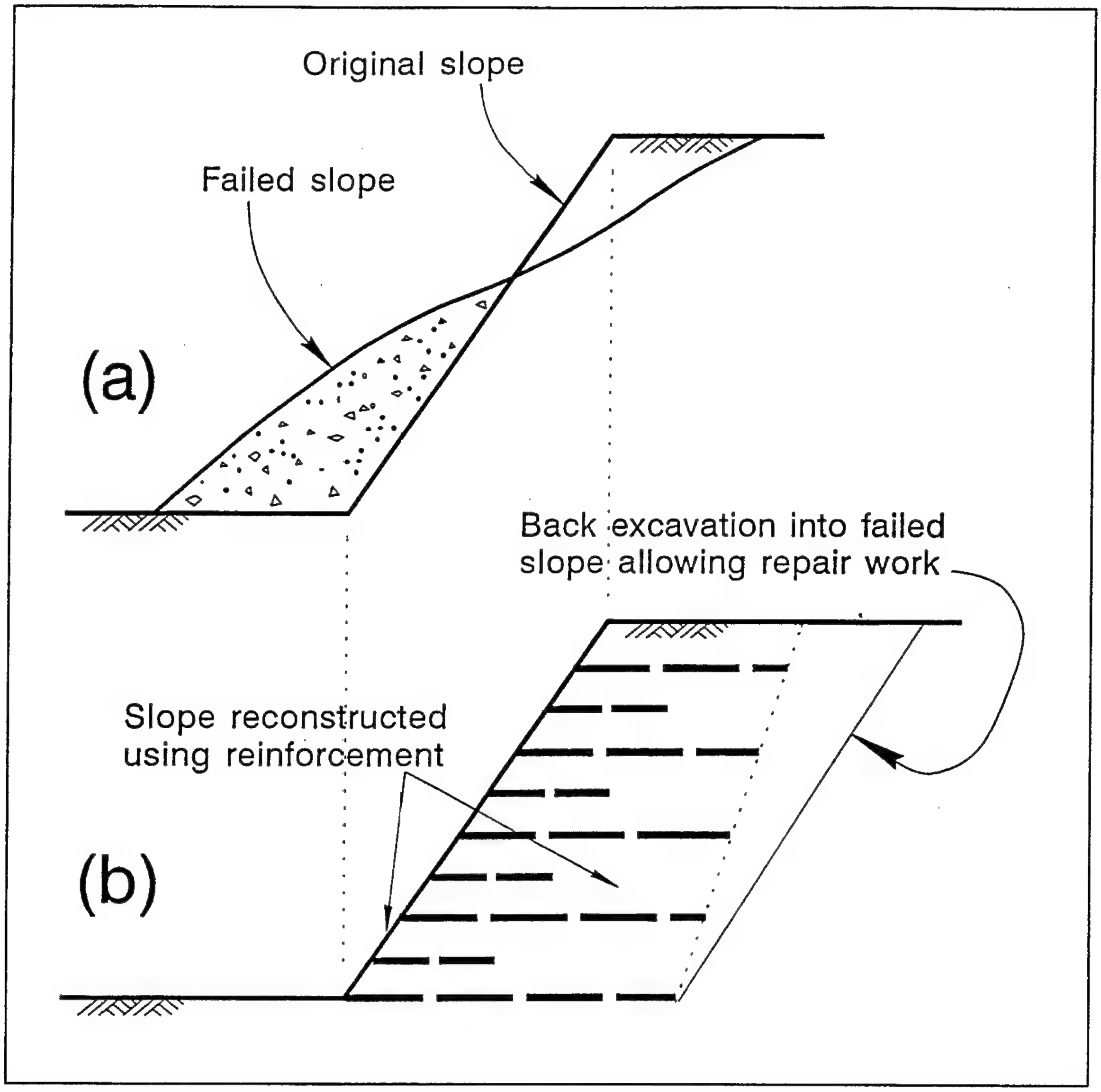


Figure 10. Slope repair (a) Failed section, and (b) Reconstructed lsope (may be steeper than, or same as, originial grade)

a. Specify reinforcement layers at lower elevations (Figure 11). Run ReSlope and verify that the calculated length as well as the various safety factors are adequate. If length is too long, lower the elevation of specified reinforcement. Conversely, if unacceptably short, run with higher specified elevations.

b. Run ReSlope again, this time for a slope H_l high (Figure 11). In this run, the reinforcement required to assure stability above point *A* (Figure 11) will be determined.

c. Specify final layout based on maximum required lengths as obtained from *a* and *b* before. Use the layout option as shown in Figure 7.

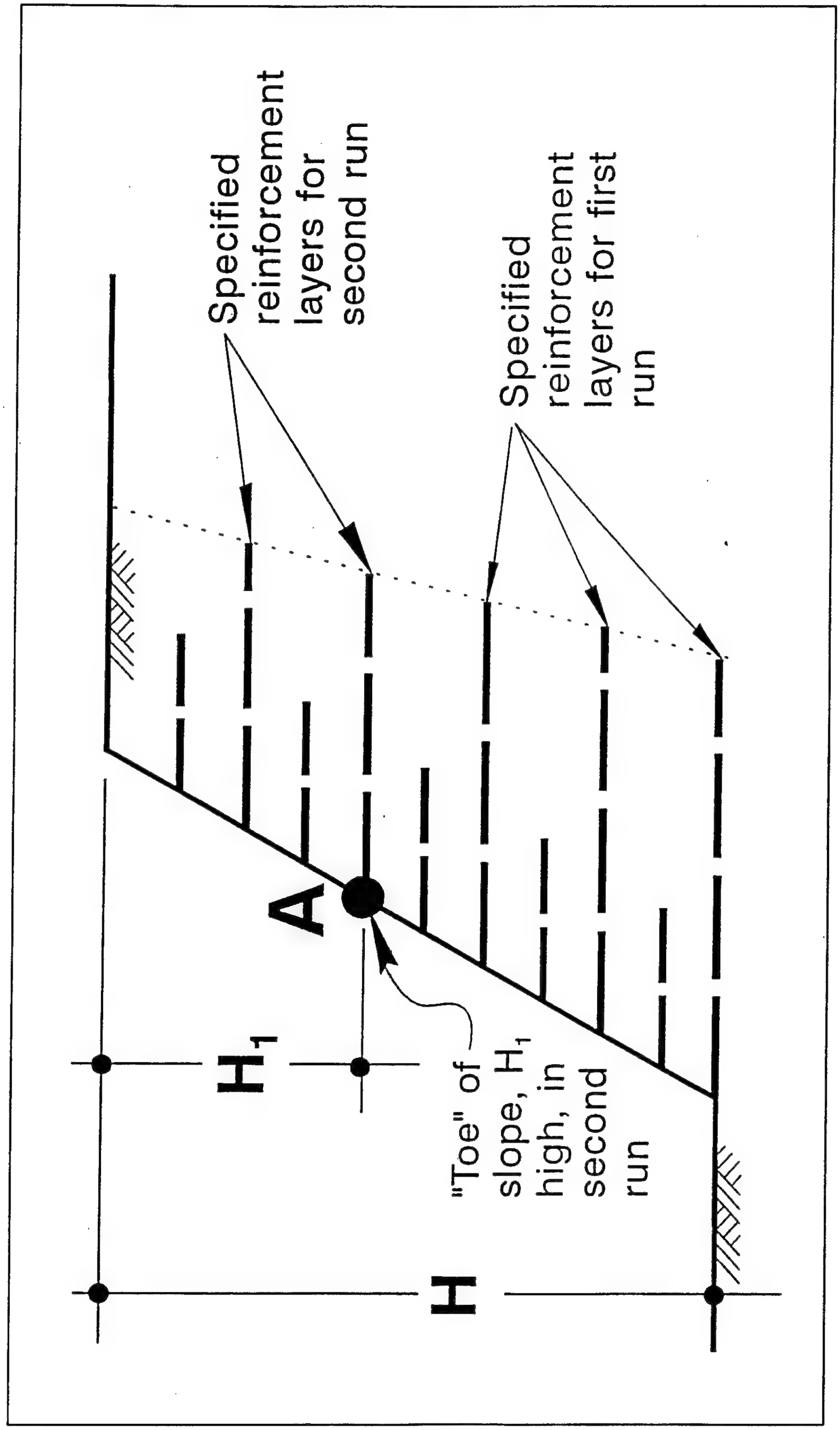


Figure 11. Procedure for running ReSlope when length of reinforcement is restricted

Note that this procedure utilizes only the lower layers to stabilize the full height of the slope. The layers above *A* provide just local stability to the upper portion of the slope. The end result is shorter reinforcement length. The trade-off is higher required strength of bottom layers.

Construction of Slope Face

Since the reinforced structure cost will depend also on the construction procedure near the slope face, it is important to consider this factor in the design phase; i.e., when selecting the slope angle. Depending on soil properties (mainly cohesion), the reinforcement spacing and the slope inclination, temporary support near the slope face may be needed to make the construction of steep slopes feasible. That is, adequate compaction near the face, without using some type of facing to support the constructed layer, may be impossible for steep slopes. A typical removable support is shown in Figure 12. A wooden board, 2 ft by 12 ft, is supported by an L-shaped bracing. The base of this bracing is a metal flange, 3 in. wide, 1/4 in. thick, and 2 to 3 ft long. A metal pipe, 12 in. high, is welded to this flange about 1 in. from its end. L-shaped bracing is placed on top of the last completed layer approximately every 3 ft. A small mound of soil can be placed on each bracing to secure its position. After placing the wooden board adjacent to the metal pipe (Figure 12), the geosynthetic sheet is placed over it. Then, the reinforced soil can be placed, evenly spread, and compacted to the desired density. If a wrapping-faced slope is constructed (Figure 12), the overhanging (unburied) sheet should be folded back and anchored into the reinforced soil. Now, the supporting board can be taken out and the bracing pulled out for reuse in the construction of the next layer. It is quite possible that manually operated compaction equipment should be used up to a distance of 3 to 5 ft from the facing. In any event, no construction equipment should be allowed directly on the geosynthetic.

The same procedure can be used also when no wraparound face is used; i.e., when the reinforcement terminates at the face. Also, for very steep slopes, left in-place welded wire mesh forms (i.e., facings) may be more economical. Information about other types of permanent or temporary facings can be obtained from geosynthetic manufacturers.

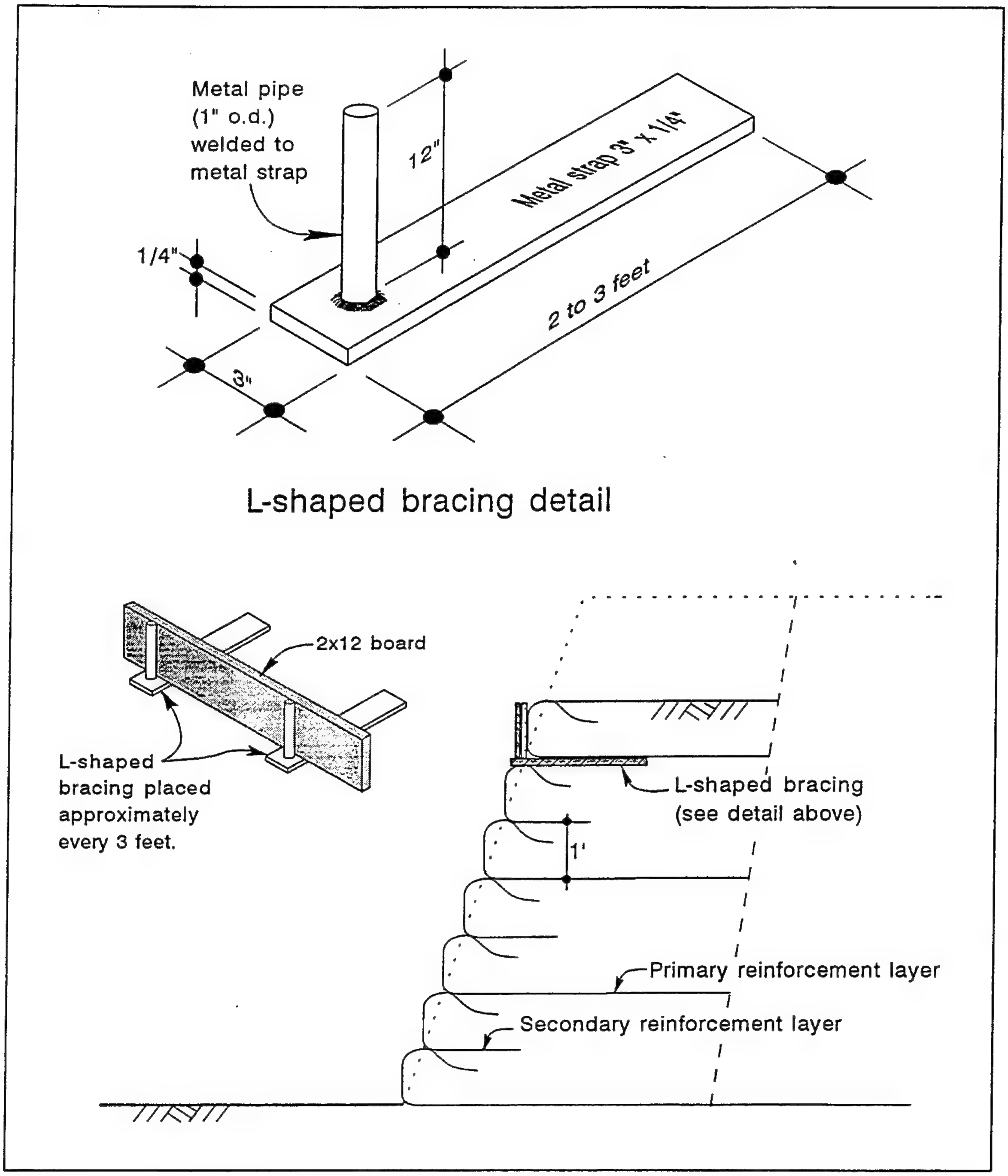


Figure 12. Removable facing support (needed for very steep slopes)

4 Conclusion

A method for the design of steep slopes reinforced with geosynthetic materials has been presented. The analyses involved in the design process are based on limit equilibrium. These analyses ensure that the reinforced mass is internally and externally stable. To make the application of these analyses practically possible, a computer program ReSlope was developed. Program ReSlope allows the user to optimize the layout of the reinforcement layers by accounting for elements such as user-specified partial safety factors, selected ultimate strength of geosynthetic, cohesive soil, pore-water pressure, external loads, and seismicity.

In addition to description of the analyses conducted by ReSlope, this report also provides recommendations regarding the selection of soil shear strength parameters and safety factors. Recognizing the limitations of limit equilibrium analysis, especially when applied to slopes comprised of materials posing different properties (i.e., soil and polymeric materials), it is recommended that the soil shear strength parameters should correspond to residual strength. It is also recommended to limit the value of cohesion used in the design of reinforced slopes.

This report presents briefly the design aspects related to erosion control of steep slopes. Also, a schematic procedure for the construction of reinforced steep slopes is illustrated. Finally, tips regarding arrest of tension cracks and an economical procedure for repairing a failed slope are given.

Program ReSlope combined with this report produces an efficient design tool for steep slopes reinforced with geosynthetic layers. This tool should be used by qualified engineers only.

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Appendix A
ReSlope: A Typical Run

Example Problem

Figure A1 shows the details of a given problem. The values of all partial safety factors are marked in this figure. ReSlope was run using the data in Figure A1, specifying the following constraints: geogrid's ultimate strength of 3,000 lb/ft, elevation of first layer at the toe level, and maximum and minimum allowable spacing of 3 and 1 ft, respectively. Option 2 in the menu was invoked to optimize the grid's elevation considering the prescribed spacing and strength constraints. A printout of a ReSlope run follows the tables and figures. Figure A2, produced by ReSlope, illustrates the designed layout of reinforcement. Table A1 shows the length of reinforcement layers varying between the length corresponding to the direct sliding (19.3 ft of bottom layer) and the value corresponding to the maximum length from compound/tieback analysis (11.8 ft obtained for layers 4, 5, and 6; see printout of results). Note that the maximum length from compound/tieback analysis is assigned to the top layer before interpolation of length of layers in-between top and bottom layers is conducted (Figure 7 for procedure). The factor of safety for uncertainties for each grid layer indicated on Table A1 is reasonable, considering the minimum value specified was 1.3. If practical, a somewhat weaker reinforcement could be specified for layers 8 through 10.

Using the previously obtained spacing (Table A1), ReSlope was run again, this time under the third option in the menu (i.e., manual specification of elevation and strength of grids). Table A2 and Figure A3 show the result when the grid's ultimate strength was specified as 6,000 lb/ft; Table A3 and Figure A4 are for a grid having an ultimate strength of 2,000 lb/ft. Doubling the grid strength to 6,000 lb/ft resulted in slightly shorter required length. However, the factor of safety against uncertainties is excessive for most layers. Also, only four layers are needed to resist compound failure as compared to seven layers before. Clearly, such a strong grid for the same spacing is wasteful.

If a weaker grid, having an ultimate strength of 2,000 lb/ft, is specified, Table A3 indicates that layers 5 through 8 are overstressed (note the arrow marks at the right hand side of Table A3; similar arrows appear on the screen

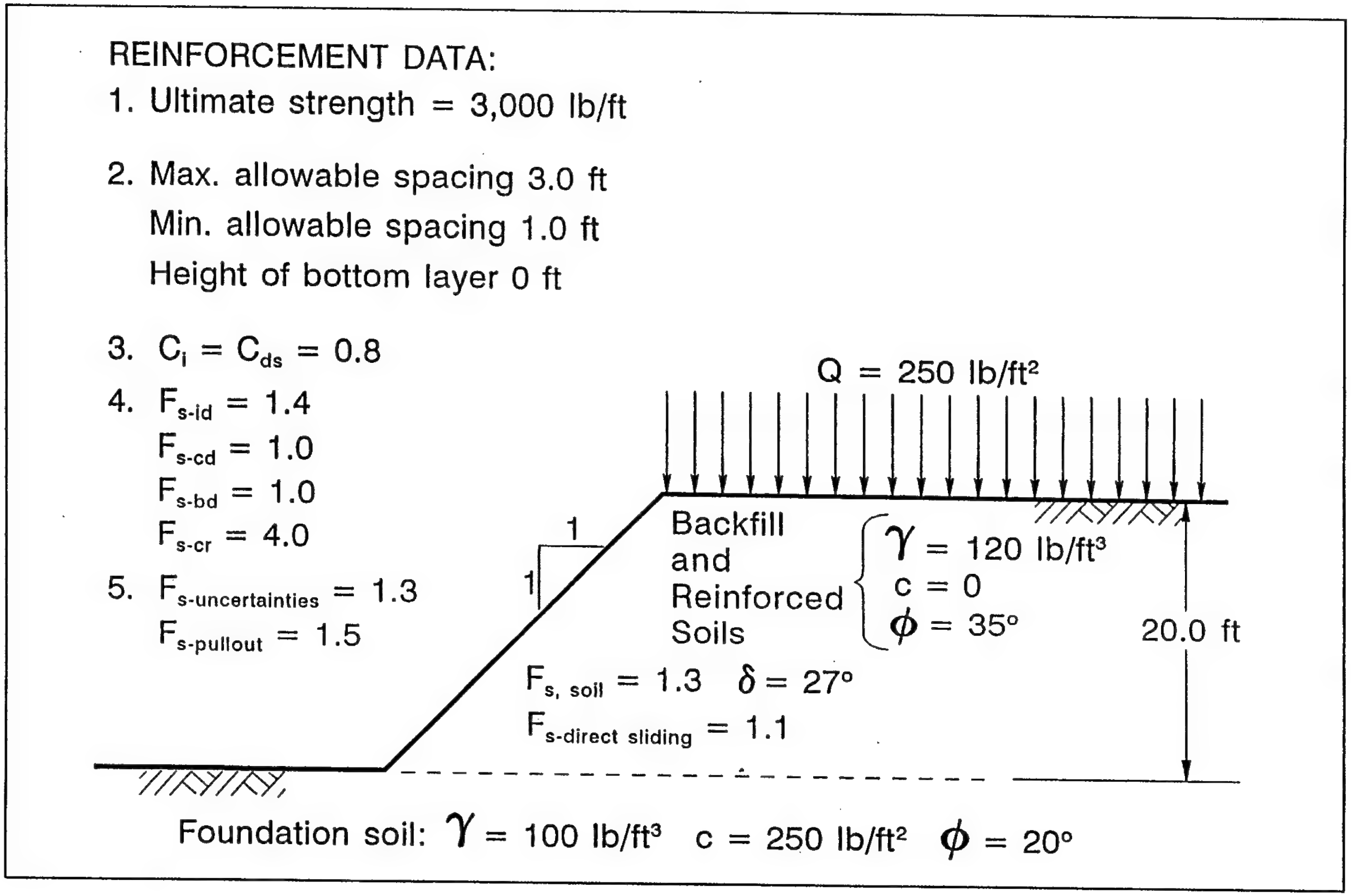

Figure A1. Data for example problem

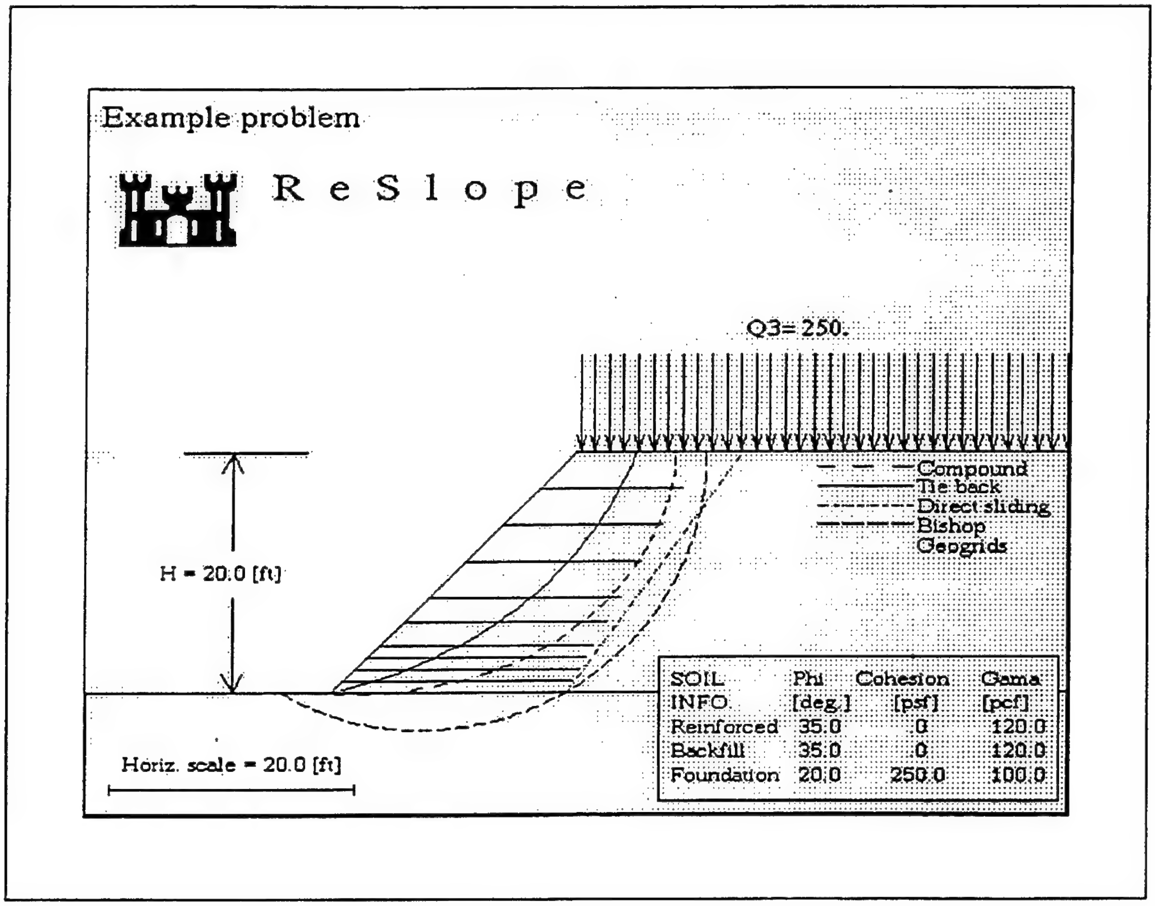

Figure A2. Designed layout (t_{ult} = 3,000 lb/ft)

Table A1
ReSlope Design (t_{ult} = 3,000 lb/ft)

Final Design Output								
Geogrid No.	Height [ft]	Grid Length [ft]	Controlling Failure Mode	Required Tr [lb/ft]	T-ult. ([1]) [lb/ft]	T-ltds ([2]) [lb/ft]	Available ([3]) Fs for Uncertainties	
1	.0	19.2	compound	412.1	3,000	535.7	>	1.30
2	1.0	18.8	compound	412.1	3,000	535.7	>	1.30
3	2.0	18.4	compound	412.1	3,000	535.7	>	1.30
4	3.0	17.9	compound	412.1	3,000	535.7	>	1.30
5	4.0	17.5	compound	412.1	3,000	535.7	>	1.30
6	6.0	16.6	compound	412.1	3,000	535.7	>	1.30
7	8.0	15.8	compound	412.1	3,000	535.7	>	1.30
8	11.0	14.5	tieback	313.6	3,000	535.7		1.71
9	14.0	13.2	tieback	215.4	3,000	535.7		2.49
10	17.0	11.8	tieback	116.6	3,000	535.7		4.59

[1] T-ult = ultimate design strength (may correspond to ultimate value or to a limit elongation value).
[2] T-ltds = long-term design (allowable) strength = T-ultimate/(Fs-id*Fs-cd*Fs-bd*Fs-cr).
[3] Fs = (Allowable design strength, T-ltds)/(Required tensile resistance, Tr).

Table A2
ReSlope Design (t_{ult} = 6,000 lb/ft)

Final Design Output							
Geogrid No.	Height [ft]	Grid Length [ft]	Controlling Failure Mode	Required Tr [lb/ft]	T-ult. ([1]) [lb/ft]	T-ltds ([2]) [lb/ft]	Available ([3]) Fs for Uncertainties
1	.0	19.2	compound	824.2	6,000	1071.4	> 1.30
2	1.0	18.8	compound	824.2	6,000	1071.4	> 1.30
3	2.0	18.3	compound	824.2	6,000	1071.4	> 1.30
4	3.0	17.8	compound	824.2	6,000	1071.4	> 1.30
5	4.0	17.3	tieback	379.5	6,000	1071.4	2.82
6	6.0	16.3	tieback	336.3	6,000	1071.4	3.19
7	8.0	15.4	tieback	412.5	6,000	1071.4	2.60
8	11.0	13.9	tieback	313.5	6,000	1071.4	3.42
9	14.0	12.4	tieback	218.0	6,000	1071.4	4.91
10	17.0	11.0	tieback	117.7	6,000	1071.4	9.10

[1] T-ult = ultimate design strength (may correspond to ultimate value or to a limit elongation value).
[2] T-ltds = long-term design (allowable) strength = T-ultimate/(Fs-id*Fs-cd*Fs-bd*Fs-cr).
[3] Fs = (Allowable design strength, T-ltds)/(Required tensile resistance, Tr).

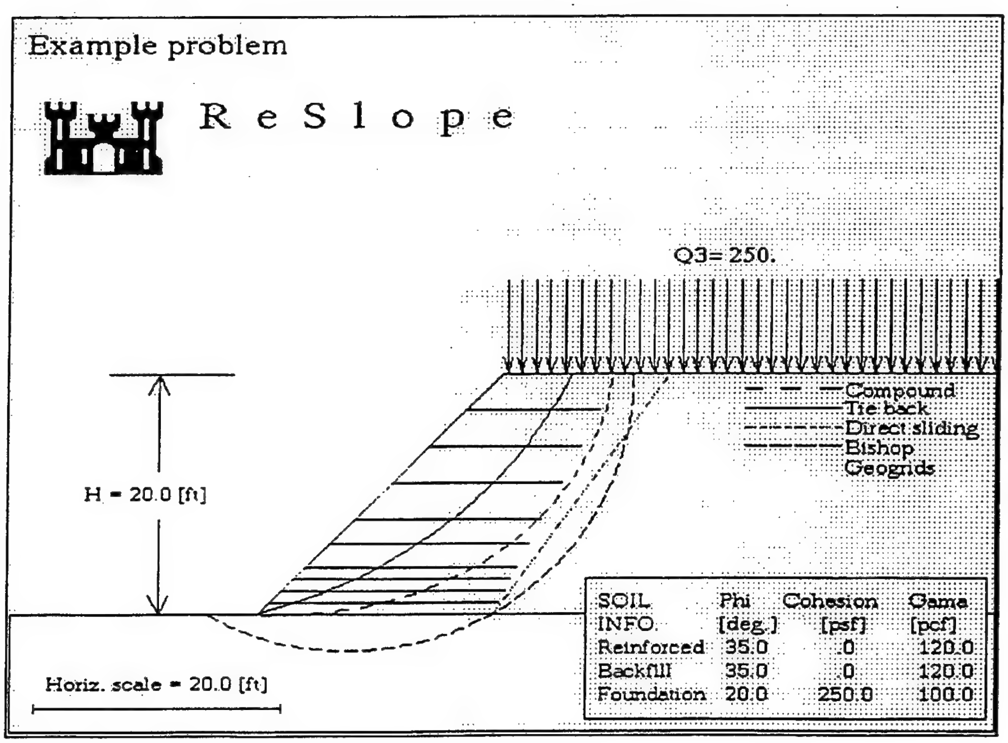

Figure A3. Designed layout (t_{ult} = 6,000 lb/ft)

Table A3
ReSlope Design (t_{ult} = 2,000 lb/ft)

Final Design Output

Geogrid No.	Height [ft]	Grid Length [ft]	Controlling Failure Mode	Required Tr [lb/ft]	T-ult. ([1]) [lb/ft]	T-ltds ([2]) [lb/ft]	Available ([3]) Fs for Uncertainties	
1	.0	19.2	compound	274.7	2,000	357.1	>	1.30
2	1.0	18.9	compound	274.7	2,000	357.1	>	1.30
3	2.0	18.5	compound	274.7	2,000	357.1	>	1.30
4	3.0	18.1	compound	274.7	2,000	357.1	>	1.30
5	4.0	17.8	tieback	379.5	2,000	357.1		.94<=
6	6.0	17.0	tieback	336.3	2,000	357.1		1.06<=
7	8.0	16.3	tieback	412.5	2,000	357.1		.87<=
8	11.0	15.2	tieback	313.5	2,000	357.1		1.14<=
9	14.0	14.1	compound	274.7	2,000	357.1	>	1.30
10	17.0	12.9	compound	274.7	2,000	357.1	>	1.30

[1] T-ult = ultimate design strength (may correspond to ultimate value or to a limit elongation value).
[2] T-ltds = long-term design (allowable) strength = T-ultimate/(Fs-id*Fs-cd*Fs-bd*Fs-cr).
[3] Fs = (Allowable design strength, T-ltds)/(Required tensile resistance, Tr).
<= Unsatisfactory Fs.

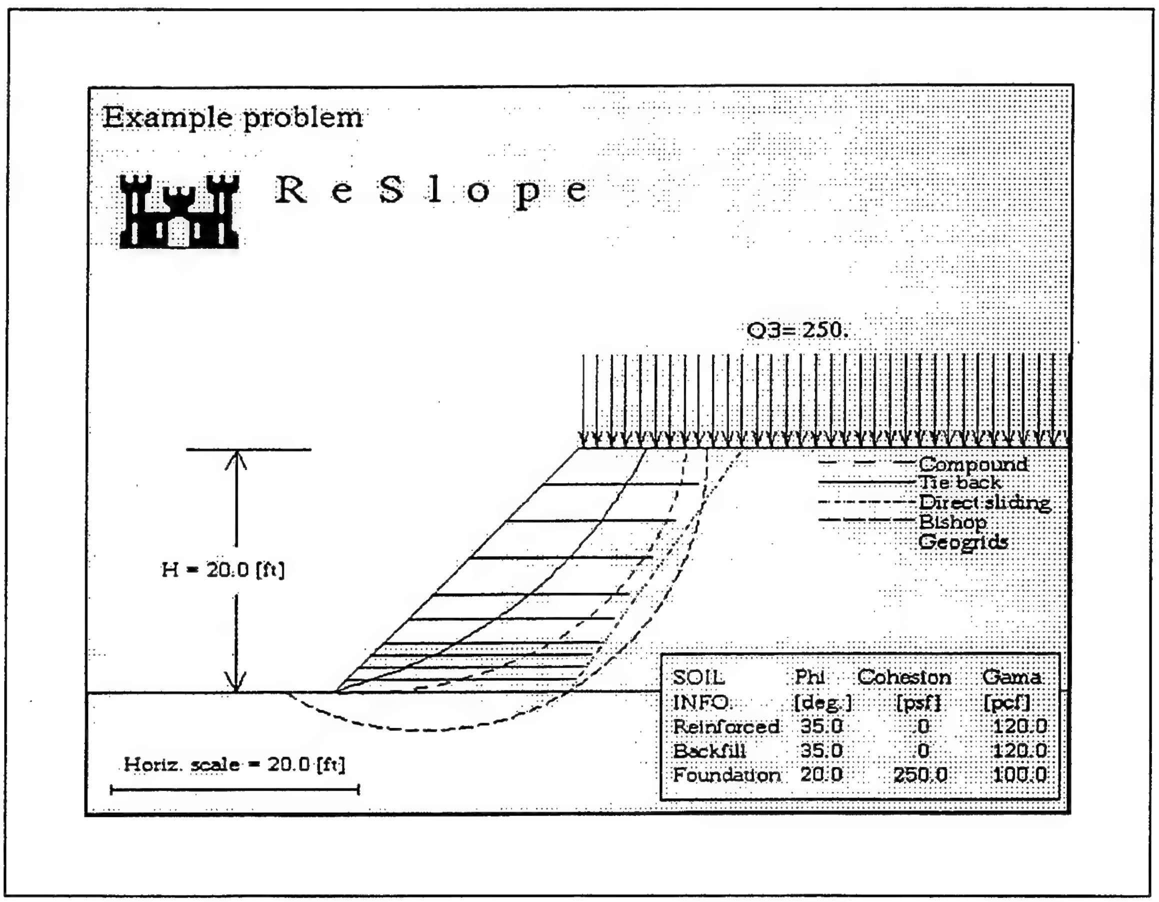

Figure A4. Designed layout (t_{ult} = 2,000 lb/ft)

showing the tabulated results; also, overstressed layers will blink on the layout screen). That is, based on tieback (i.e., internal stability) analysis, the stresses induced in these layers will render factors of safety less than the specified value of 1.3. Consequently, an unsafe situation is created in which some layers may locally be ruptured. Such ruptures may trigger a global collapse. Clearly, the reinforcement is too weak for the specified spacing. The solution is to specify layers that are more closely spaced (i.e., more reinforcement layers overall). Alternatively, a stronger reinforcement (e.g., 3,000 lb/ft) could be specified.

The example problem demonstrates the versatility of ReSlope as a design tool. The user can easily design an economical layout. It should be pointed out that the design output includes only the primary reinforcement layers. See Chapter 3, main text, for discussion of the secondary layers.

Printout of Results

A printout of a ReSlope run is presented on the following pages.

R e S l o p e

Analysis of Geogrid Reinforced

Steep Slopes

Project Title:	Example problem
Project Number:	1
Project Designer:	Dov
Input File Name:	EXAMPLE.IN
Date:	08/24/95
Time:	21:04:57

«««««««««««■■■■■■■■■■»»»»»»»»»»»»
Design Philosophy and Program Developed by:
Dov Leshchinsky, Ph.D.
33 The Horseshoe
Newark, Delaware 19711
Tel. (302) 368-3197
«««««««««««■■■■■■■■■■»»»»»»»»»»»»

ReSlope

Analysis of Geogrid Reinforce
Steep Slopes

Project title:	Example problem
Project No.:	1
Project designer:	Dov
Project description:	This is to demonstrate a run using ReSlope. The effects of selecting a geogrid strength will be shown.

GEOMETRY AND LOADING DATA

Height of slope, H [ft]	20.0
Slope angle, i [degrees]	45
Horizontal Length, A [ft]	0
Horizontal Length, B [ft]	0
Backslope Angle, BETA [degrees]:	0
Angle of slope below reinforced zone, ALPHA [degrees]	0
Surcharge load over A, Q1 [psf]	0
Surcharge load over backslope B, Q2 [psf]	0
Surcharge load away from backslope, Q3 [psf]	250

SOIL DATA

REINFORCED SOIL:	Internal angle of friction, phi [degrees]	35
	Cohesion [psf]	0
	Moist unit weight [pcf]	120
BACKFILL SOIL:	Internal angle of friction, phi [degrees]	35
	Cohesion [psf]	0
	Moist unit weight [pcf]	120
FOUNDATION SOIL:	Internal angle of friction, phi [degrees]	20
	Cohesion [psf]	250
	Moist unit weight [pcf]	100

GENERAL DATA

Assumed angle of interwedge force (direct sliding analysis), DELTA [degrees]	27
Horizontal seismic coefficient, Cs	0.0
Cs was NOT applied to the reinforced soil mass and surcharge above it	
Maximum allowable penetration depth for Bishop's circle [ft]	40.0

ReSlope

Analysis of Geogrid Reinforce
Steep Slopes

Project title:	Example problem
Project No.:	1
Project designer:	Dov
Project description:	This is to demonstrate a run using ReSlope. The effects of selecting a geogrid strength will be shown.

SPECIFIED SAFETY FACTORS

Factor of safety on soils shear strength	1.3
Factor of safety for direct sliding	1.1
Factor of safety for grid uncertainties	1.3
Factor of safety for grid pullout	1.5

GEOGRID DESIGN DATA

Pullout interaction coefficient (reinforced soil), Ci	.8
Pullout interaction coefficient (foundation soil), Ci	.8
Direct sliding coefficient (reinforced soil), Cds	.8
Direct sliding coefficient (foundation soil), Cds	.8

GEOGRID SPECIFIED SAFETY FACTORS

Fs-id, factor of safety for installation damage	1.4
Fs-cd, factor of safety for chemical degradation	1.0
Fs-bd, factor of safety for biological degradation	1.0
Fs-cr, factor of safety for creep	4.0

Input data file: EXAMPLE.IN Date printed: 08/24/95 Time printed: 21:04:57

R e S l o p e

Analysis of Geogrid Reinforce
Steep Slopes

Project title: Example problem
Project No.: 1
Project designer: Dov

FINAL DESIGN OUTPUT

Geogrid #	Height [ft]	Grid Length [ft]	Controlling Failure Mode	Required Tr [lb/ft]	T-ult. (*) [lb/ft]	T-ltds (**) [lb/ft]	Available (***) Fs for Uncertainties
1	.0	19.2	compound	412.1	3000	535.7	> 1.30
2	1.0	18.8	compound	412.1	3000	535.7	> 1.30
3	2.0	18.4	compound	412.1	3000	535.7	> 1.30
4	3.0	17.9	compound	412.1	3000	535.7	> 1.30
5	4.0	17.5	compound	412.1	3000	535.7	> 1.30
6	6.0	16.6	compound	412.1	3000	535.7	> 1.30
7	8.0	15.8	compound	412.1	3000	535.7	> 1.30
8	11.0	14.5	tieback	313.6	3000	535.7	1.71
9	14.0	13.2	tieback	215.4	3000	535.7	2.49
10	17.0	11.8	tieback	116.6	3000	535.7	4.59

(*) T-ult. = ultimate design strength (may correspond to ultimate value or to a limit ellongation value).
(**) T-ltds = long term design (allowable) strength = T-ultimate/(Fs-id*Fs-cd*Fs-bd*Fs-cr)
(***) Fs = (Allowable design strength, T-ltds)/(Required tensile resistance, Tr)

ReSlope

Analysis of Geogrid Reinforce
Steep Slopes

Project title: Example problem
Project No.: 1
Project designer: Dov

RESULTS OF COMPOUND AND TIEBACK ANALYSES

Geogrid #	Height [ft]	Total Length [ft] (*)	Minimum Anchorage [ft]	T-compound: Available [lb/ft]	T-tieback Required [lb/ft]	Controlling Mode of Failure
1	.0	5.6	1.1	412.1	241.1	compound
2	1.0	9.4	.7	412.1	230.3	compound
3	2.0	11.4	.5	412.1	219.0	compound
4	3.0	11.8	.5	412.1	206.8	compound
5	4.0	11.8	.5	412.1	375.9	compound
6	6.0	11.8	.5	412.1	333.6	compound
7	8.0	11.4	.5	412.1	411.8	compound
8	11.0	11.0	.4	412.1	313.6	tieback
9	14.0	9.7	.4	412.1	215.4	tieback
10	17.0	7.8	.3	412.1	116.6	tieback

(*) Total length (including achorage) satisfying all specified safety factors, considering slip surfaces passing through the reinforced and backfill soils.

ReSlope

Analysis of Geogrid Reinforce
Steep Slopes

Project title:	Example problem
Project No.:	1
Project designer:	Dov

SUPPLEMENTAL RESULTS

==

Required length of bottom layer to assure the specified Fs-direct sliding = 1.1 is 19.2 feet.

Maximum length from compound and tieback analyses to assure Fs-uncertainties = 1.3 and Fs-pullout = 1.5, is 11.8 feet.

NOTE #1: The traces of the outer-most log spirals for tieback and compound failure are defined.

by Xc=	10.1 ft, Yc=	37.6 ft, A=	33.8 ft
and Xc=	16.7 ft, Yc=	26.8 ft, A=	23.4 ft, respectively.

Deepseated safety factor, Fs-deepseated, based on Bishop's analysis, is 1.5. The critical circle is forced to pass outside the reinforced zone as defined by the bottom grid layer; its maximum potential depth is limited to 40. feet.
The critical circle is at: Xc = 7.6, Yc = 20.0,
Radius = 23.1 feet.

In case the crest elevation is above H, ReSlope assumes a tension crack to develop between the crest and H (see screen of slip surfaces).

NOTE #2: To obtain satisfactory Fs-deepseated, please run ReSlope again with larger specified values of Fs-direct sliding. This will force deeper circles which may yield larger safety factor.

Tieback/compound slip surfaces are not restricted from penetrating the foundation soil.

Notes in Results

The results, appearing under the heading Supplemental Results include two brief notes that require some elaboration. The first note provides data, if desired, for hand calculations to verify the correctness of some of the results. The second note suggests a methodology to extend the length of the reinforcement so as to assume satisfactory stability against deepseated failures.

Note 1 provides the information needed to compute the trace of the critical log spiral surface; i.e., the three parameters x_c, y_c, and A are given. Follow the parametric equations, superimposed on Figure 2, main text, to calculate the x and y coordinates of points that define the log spiral trace. Two sets of parameters are printed; one representing the outer-most log spiral for the tieback analysis (Figure 3, main text) and the second depicts the outer-most log spiral for the compound analysis (Figure 5, main text, Step 2, surface passing through point G). These log spirals are also plotted by ReSlope on the layout screens. Using the trace and parameters of the log spirals, one verify the correctness of ReSlope's computed reactive forces by substitution into the moment equilibrium equation, written about the log spiral pole, as shown explicity in Figure 2, main text, i.e., $\Sigma M_p = 0$. Substitution of the respective computed results for either the case of log spiral should render ΣM_p reasonably close to zero. It should be pointed out that hand calculations of the direct sliding results can be done straightforward by following the procedure described in the text and shown in Figure 6, main text. If it is necessary to verify the results via hand calculations, use the program output, L_{ds}, to check whether the hand calculated $F_{s\text{-}ds}$ is indeed the same as that produced by ReSlope. Clearly, hand calculations in the context of reinforced soil are laborious and tedious. Alternatively, the traces of the various slip surfaces can be utilized as input when running another computer program (e.g., UTEXAS3) as a check on the safety factors. It is much simpler, however, to use the layout produced by ReSlope (i.e., length, spacing, and strength) as an input for another program and verify whether the resulted safety factors, calculated based on a different limiting equilibrium method, are close to those prescribed for ReSlope. Such a check provides comparison between two different approaches and, therefore, should increase the confidence in the results.

Note 2 appears immediately following the results of Bishop's (Edris and Wright 1992) stability analysis assessing deepseated failure around the reinforced soil. In Bishop's analysis, the reinforcement length, as obtained from tieback, compound, and direct sliding analyses, is used as an input data and the critical slip circle and its associated $F_{s\text{-}deepseated}$ are sought. The calculated safety factor then may not be satisfactory. To remedy this potential problem, one possible solution is to extend the length of the reinforcement. However, ReSlope does not allow for such direct control on length. To overcome this limitation, the user can run the program again but this time with a larger specified $F_{s\text{-}direct\ sliding}$. By a trial and error process, the required safety factor for deepseated failure can be achieved. This, however, will be at the expense of a larger than needed factor of safety against direct sliding mode of failure.

Appendix B
ReSlope: Structure of Program

Figure B1 shows, in an illustrative fashion, the structure of ReSlope. It gives an overview of the menu and submenus. The actual details of the analyses are presented in the body of this report. Consequently, Figure B1 is simplified and self-explanatory.

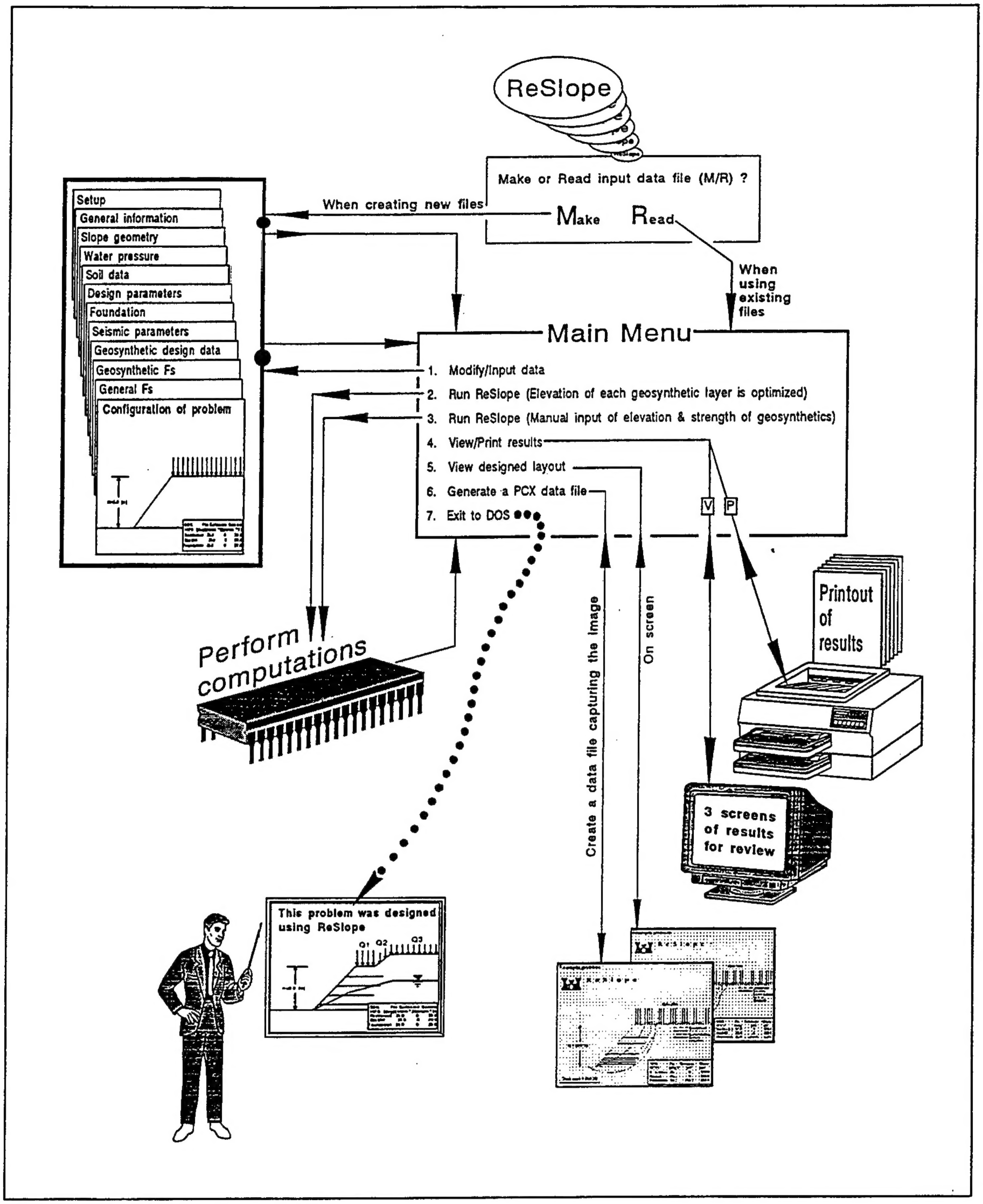

Figure B1. Illustrative flow chart of program ReSlope

Appendix C
Computer System Requirements and Program Loading

To run properly, ReSlope requires a PC compatible system with at least 2MB RAM. The PC should have a 386 or higher processor; a math coprocessor is practically necessary to run the program. The display should be VGA or better, have 640 by 480 pixels or higher. To obtain maximum effects, color display is recommended. The operating system should be DOS 4.00 or higher. Alphanumeric results can be printed using any printer that is compatible with the system and is connected to the first parallel port; i.e., LPT1. If the printer is graphically compatible with the system through DOS, the graphical image on the screen can be sent to the printer using the Print Screen key; in this case, however, change the display to black and white using the toggle in System Setup in submenu (use program help commands for details). Since the layout screen can be captured as a PCX data file, the user can access this file upon exiting ReSlope with most commercially available graphics software, edit the image if necessary, and then print it out using the particular software utilized. Such graphics software allows the user, in a friendly fashion, to make the computer graphically compatible with most printers. For maximum output quality, a laser printer is recommended.

The following subprograms are included in the program's diskette: RESLOPE.EXE, DOSXMSF.EXE, RXX.EXE, MODERN.FON, and TMSRB.FON. To facilitate runs, copy all files from the diskette to the hard disk (i.e., drive C) following this procedure:

a. While in DOS and in drive C, create a dedicated directory called RESLOPE by typing at the prompt C> the following: MD RESLOPE.

b. Enter this directory by typing: CD RESLOPE.

c. Place the diskette containing all the subprograms in drive (or drive B).

d. Type, at the prompt C:\RESLOPE>, the following: COPY A:*.* (or COPY B:*.*.).

e. Once all subprograms are copied, the program can be run by typing: RESLOPE.

Each time the program is run, one has first to enter the directory RESLOPE in DOS. Entering this directory from DOS prompt C> is achieved by typing CD RESLOPE (see Step b above) which means Change Directory to RESLOPE.

REPORT DOCUMENTATION PAGE

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This report is available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161. Computer diskettes of the ReSlope computer program are available from the U.S. Army Engineer Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report presents a method for the design of geosynthetic reinforced slopes. A computer program ReSlope was developed to allow the user to optimize the design by accounting for elements such as user-specified partial safety factors, geosynthetic ultimate strength, cohesive soils, pore-water pressure, external loads, and seismicity. This report provides recommendations regarding selection of soil shear strength parameters, safety factors, and practical specifications for reinforcement layout. Design aspects related to erosion control and construction are also discussed. Finally, tips regarding arrest of tension cracks and an economical procedure for repairing a failed slope are given.

14. SUBJECT TERMS

Computer analysis	Slope repair
Erosion control	Slope stability
Geosynthetics	Tension cracks
Reinforced soil	

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